IRE Transactions

on Reliability and Quality Control

Volume RQC-9 September, 1960 Number 2

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PUBLISHED BY THE

PROFESSIONAL GROUP ON RELIABILITY AND QUALITY CONTROL

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Annual Fee: $3.00

IRE TRANSACTIONS®

on Reliability and Quality Control

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PRINTED IN U.S.A.

Research and Development Aspects of Reliability

VICE ADMIRAL J. T. HAYWARD†

It is indeed a pleasure to be here tonight to talk to ou on the subject of research and development and eliability. Some people might question it but relia- ility is really a constant and ever-present companion f any research and development program. The only eal product out of any such program is usable hard- vare , and to be useful it must be reliable.

As you people who live with the problem really now, there are many degrees of reliability. They ary from our requirement that the car start every ime to the long involved countdown on one of the nost complicated missiles. We who have been to a var, or wars, have a great deal of difficulty visuali- ing some of our more complex systems ever being eliable weapons of war.

Reliability extends into all the fields of warfare. Mobility, communications, surveillance, firepower nd logistics are all places in modern warfare. Where lack of reliability can cost dearly. If anything, nodern technical progress has made the penalty of ack of reliability even higher than ever before in var.

At this point, I am sure a definition is in order o that we will understand each other on the subject. Ve define reliability as the quality of a device or its omponents which permits unfailing performance in ll the environments of operations. Another defini- ion might be the probability of a device performing ts purpose adequately for the period of time intend- d under the operating conditions encountered. I am ure these are not new to you.

Another definition which is really a general one s the reliability of something is the measurement of he interaction between the strength of the object and he stress applied. This is using the word stress vith a very general meaning. This could also be used n individuals. As you all know, quality control gets nixed up in this discussion; we should also try and efine that at this point. We call it that function which nforces compliance with engineering instructions, vhether given by drawing, specification, or other nanner.

So you see, as far as reliability is concerned, quality control only insures that the engineering dis- closure is really carried out - and if the disclosure is not a reliable one, all the quality control in the world will not make it so.

Now let us get at some of these problems that face us in the Navy on this subject. As I said before, the only reason for research and development program is the production of usable and reliable hardware. The Navy has all the problems of the other services plus the fact that these are compounded by environ- ment, namely the sea. We fly airplanes, go beneath the sea and travel on its surface. We have amphibious operations. These all require reliability of the high- est order in the equipment involved.

I am sure you have the same reactions I have when you see the full scale picture on the front page of the Washington Post with the missile in a raging sea of fire still on the test stand. Your disappointment is nothing to the results if this happens in war.

Never forget that war is never orderly and never goes as planned, whether one has a Bismark or a Joint Chiefs of Staff. If one word were used to des- cribe war, it would be the word confusion. So we in the research and development business must start right from the beginning and see that what we are trying to put together as a system can be made a reliable one under our previous definition. How does one really go about doing this is the question. If I were to give one answer to this, it would be on the subject of components. Components have been com- pletely overlooked in the glamour of the many large systems. Admittedly, it has been easier in the past to obtain money for many large systems but the re- sults have shown that we should have paid more atten- tion to our homework on the components. One can not invent on schedule, as we have found to our dismay.

Economy of effort dictates that each new system should constitute a significant advance over its pre- decessor. If this is to be accomplished economically, we must break these systems down to the smallest

Statler Hotel, Washington, D.C.

components on which significant experiments can be made and then do our gambling on these components. Where the payoff is large and the cost of the gamble is small, it is wise to take the chance even when the possibility of success is small, perhaps even less than one in ten. It is not economical to duplicate the development of large systems, but this gambling type of research on components or new concepts in combination with new components can give us results.

The insidious side of this component work can be seen if one considers a new system now being designed, which has a lot of new components arranged both in series and parallel. If any of these components have not been designed or built, there is the question, "Can they be made to work reliably?" The more radical, the greater the doubt. Any modern system will require that a large number of these work if the system is to operate. If there were ten such components and each had a fifty-fifty chance of working, the chance that the system would work would only be about one in a thousand. As a systems designer, I am sure you would demand only proven components. This faces you with the question of just what advance you will make in the system. You can all see that reliability plays its part all the way through the process.

So you see that in the research and development programs, the reliability starts with the lowest component, and that the way of progress starts there also. For if one has all the necessary components, he can then put together his system in a relatively reasonable time with a strong feeling that it will turn out to be reliable.

Now after we have done all our homework and the system starts to be delivered, we once again run an independent evaluation on it with the people who will have to operate it. This is done in the environment for which it was designed. We have a large investment in our operational test and evaluation force just to perform this evaluation function. It is amazing the number of equipments that fail at this actual test. This covers everything from fuzes to radars, and even complete airplane systems. As modern systems are large and expensive, it is not possible to run a complete separate operational evaluation on all of them. We therefore bring our operational people in early on the project and they live with the system during all its growing phases and the technical evaluation. This is all done in order to get reliable and useable hardware and is a tremendous part of our research and development effort.

Let me close by saying that if reliability is not brought in at the research and development phase of any system, it will probably never be an operational useable one. Unfortunately we have had too many examples in recent years of this happening.

Reliability Responsibilities*

JULIAN K. SPRAGUE†

The evolution of warfare from an art to a science ıas led to the development of weapons systems of such complexity that the design concepts, and dependability, of parts and systems of World War II and Korean War vintage are no longer adequate to the task. This has highlighted the problem of reliability of both systems and the parts that go to make up these systems, and innumerable words have been spoken and written regarding this problem in the last five years.

You will note from the program that my subject oday is Reliability Responsibilities. Reliability and responsibility are indeed terms that belong together. Unfortunately, in far too few instances have reliability and responsibility been tied together despite the act that, like virtue, everybody is for reliability.

Many definitions of reliability have been proposed; one I like as well as any for military equipment is hat of the Bell Telephone Laboratories, which says, "Reliability is the probability that an equipment will perform its intended function for a specified period of time when used in the manner and for the purpose intended." From Webster we find that responsibility s accountability, including moral accountability.

It has been stated that defense of the nation is everyone's responsibility, not just that of the military services. Much has been said also about the various organizations which share in responsibility for reliability, from the Department of Defense itself down through the military departments, prime and subcontractors, and suppliers of parts and materials. No one will argue that all of these are involved with the problem of reliability, but it has proven very difficult to get agreement among them as to what their various responsibilities actually are. I would like to look at reliability from the standpoint of the major functional responsibilities hat seem to be involved. It should be recognized hat the ways these functional responsibilities are carried out will differ with the particular product and the particular military or industrial organization, but all of these organizations must accept a share of the responsibility for each aspect of the problem.

Let me define the first major functional responsibility as the responsibility for specifying reliability. There are, of course, a number of ways of determining what reliability is needed, and how it is to be achieved. It is pertinent to try to gain an understanding of the contributions expected of the various groups who share this responsibility.

Starting at the top, it is the responsibility of the Department of Defense to emphasize to the entire military establishment that quality and reliability are the most important ingredients of weapons systems that will do the job expected of them. Such emphasis precludes excessive concern with unit cost as a valid criterion in weapons procurement. These principles must be adhered to not only through the insurance of directives, but must also be implemented with the necessary funding. Further, the Department of Defense must insure that directives issued on this vital subject will receive uniform interpretation among the military departments. This will effectively eliminate competitive programs between two or more departments. Turning now to the military departments themselves, it is certain that they must comply with the directives of the Department of Defense if any reliability program is to succeed. One of their most important responsibilities entails the development of complete and uniform specifications, without loopholes, which will apply the same set of ground rules to all suppliers. This will prevent clever individuals from making compromises in the interest of lower cost but at the sacrifice of reliability. Toward this end, the executives of the departments, through their specification programs, must encourage maximum standardization of highly reliability components.

Another important responsibility of the military departments is the dissemination of all information available to them on parts, materials, and design practices as they bear on systems reliability. This distribution should be not only to those within the department charged with application approvals, but also among those responsible for equipment design in the plants of their prime and subcontractors.

The primary responsibility of the equipment pro-

* Presented at the Sixth National Symp. on Reliability and Quality Control, Location; January 11, 1960.
† Author's Affiliation?

ducer in specifying reliability is to instruct his systems people, including product designers, that they are to make an honest, all-out effort to achieve the reliability levels called out by their contracts, and that the attainment of these reliability levels is more important than the saving of a few dollars in the cost of the equipment. Beyond this, the equipment producer must require that the quality assurance procedures of the applicable parts specifications, whether they be military or company specifications, be completely followed by all subcontractors and suppliers. This must, of course, include the conducting of all control acceptance testing. He must further require that all subcontractors and suppliers furnish proof that the specification requirements have been met. Here I wish to point out that we all recognize that reliability cannot be tested into a material, part or assembly; however, in the absence of an adequate acceptance test program there is certainly no assurance that the desired reliability has been achieved.

Producers of parts and materials have a peculiarly vital role in the achievement of reliability, because the reliability of equipments can be no better than the reliability of the parts from which they are made. It is also in the area of parts and materials that perhaps the least is known concerning the mechanisms of failure. It is in this area that the military establishment will have to lean most heavily on the parts manufacturer for support in the attainment of its reliability goals. For his part, the parts and materials producer must be willing to undertake within his own organization the disciplined, tough approach required to achieve the desired result. This approach will include engineering studies of modes of failure and the means of overcoming them. When this information is available, and only when it is available, the parts and materials producer will be able to specify designs for his products which are consonant with the reliability objectives of the total system.

My second major functional responsibility is that of producing reliability. Whether it be in equipment or parts, a strongly stated management policy, backed up by competent engineering, production discipline, and quality assurance procedures, is the key to producing reliability. Let us assume at this point that the military departments, in exercising their responsibility, have specified that lot-by-lot control through testing is a firm contractual requirement. It then becomes the responsibility of the producing contractors to comply with this requirement. To do so they must make it perfectly clear to all of their vendors that no deviation from the lot-by-lot controls will be permitted, even though use of such controls results in a higher unit purchase cost for the part or material. Unfortunately, the practice of waiving test requirements and lot-by-lot control procedures in the interest of lower cost is very widespread today.

A major limitation on our collective ability to produce reliability is the existing shortage of appropriate environmental and quality acceptance test equipment and personnel, without which the achievement of reliability cannot be proven. It is the responsibility of the equipment and parts producers to remedy this shortage, but it is equally the responsibility of the military departments and the Department of Defense to bear an appropriate share of the cost of these essential facilities.

The Government can help to attain reliability by requiring the use of highly reliable subassemblies, parts, and materials in the same manner that they recently required the use of highly reliable tubes by their contractors. They can also help by fostering sound, long-range research and development programs aimed at a general and systematic upgrading of reliability. Too much of our present research and development effort is concentrated on breakthrough research. This frequently results in the development of systems or parts for specific applications. The high cost of this type of work is probably justified, but it seldom has general application, nor does it serve to increase the reliability of standard parts and materials.

My third major functional responsibility is for procuring reliability, and differs significantly from specifying and producing reliability. For no matter how well reliability requirements are spelled out, or how good the production techniques evolved to meet these requirements, reliable parts and equipments will not be produced without more enlightened procurement practices than are now in general use.

Except for negotiated contracts and certain contracts where bidding is restricted, present day procurement requires open competitive bidding. This results in pitting known high quality producers economically against manufacturers who have not demonstrated a capability for producing to the required standards. I do not propose that we scrap our system of open competitive bidding; but I do suggest that it be modified by suitable restriction on those contracts which require high levels of reliability. This would limit bidding to those manufacturers who have demonstrated their ability to produce to required reliability levels.

There are a number of ways in which modified competitive bidding can be administered. One way would be to grade the manufacturer on the quality level of his products, and on his record in complying with contractual requirements. Performance of

ıis product could be determined, for example, by ıdopting a measure of time between failures, suitably weighted for differences in specification levels ınd contract volume. Then, in the awarding of future contracts, both the grade and the bid price would be factors in a formula developed for selecting the successful bidder. Obviously, details for the implementation of such a procedure will require extensive study; for example, in the case of a company with many semiautonomous departments, it may be essential to rate the departments individually, rather than to attempt to evaluate overall corporate performance.

I believe it is generally recognized that the prime responsibility for acceptance or rejection of electronic parts must remain with the equipment contractor. To assist him in this task, the Government has developed the Qualified Products List. This list has been used by government procurement officers as well as by government contractors to select parts for use in end equipments. Over the years, abuses have arisen in the application of the Qualified Products principle, in that many manufacturers have come to believe that if they buy any listed part, their responsibility for using parts of acceptable quality has been fully discharged. Nothing could be farther from the truth, because it is the sole intent of the Qualified Products List to indicate that a given manufacturer has, or had, the capability to produce satisfactory parts, and that he has at some time or other designed and produced a limited number of sample parts of acceptable quality. Conversely, the Qualified Products List does not guarantee that a given manufacturer either has a production capability, or if he does, that he consistently maintains a satisfactory quality level in his production. In the light of today's reliability demands, reliance upon such a system is a totally inadequate means of assuring a satisfactory product. I recommend that this system be revised to incorporate several basically new requirements:

First, to maintain approval, a parts or materials manufacturer not only must have made at some time a quantity of the item which met the specification requirements, but also, based on acceptance inspection records kept in accordance with the specification, his product must continue to meet these requirements. This can be accomplished only through lot-by-lot control. Second, that the manufacturer of the approved parts maintains, as shown by periodic inspection by the qualifying agency, the necessary test facilities and in-plant process controls to assure his ability to continue compliance with the specification requirements in the future.

Gentlement, I have been discussing with you the major responsibilities for reliability and the roles which must be played by the various organizations in industry and government. You will note that collectively they form a chain. A break in any link will break the reliability chain. Inasmuch as this Symposium is a reliability conference, I know that each of you is here in the interest of doing your part to help realize the reliability which our national survival so urgently requires. Those of you who have diligently worked to achieve reliability in your various areas of endeavor know that the task ahead is no easy one. It can never be accomplished if we are to let prejudice, pride of invention, or organizational self-preservation interfere with the achievement of our goals.

A System Reliability Analysis*

R.T. LOEWE†

INTRODUCTION

How much effort and money should be expended on reliability? How can system reliability be related to system performance? To answer these questions, a good system reliability figure of merit is needed. This paper suggest such a figure of merit. The discussion covers, in order: system reliability figures of merit, a basic analysis model, redundancy, assumptions and refinements, trade-off analyses and conclusion.

SYSTEM RELIABILITY FIGURES OF MERIT

Two characteristics of systems help determine the most appropriate reliability figure of merit. They are 1) whether or not maintenance can be performed, and 2) whether or not different failures degrade system effectiveness by different amounts. Where no maintenance is possible, the over all failure rate is useful. Where maintenance is possible, the percent down-time is useful. However, if these alone are used as figures of merit, every failure is given the same weight regardless of the degradation of system effectiveness which it causes.

Thus, the effect of failures must be weighted where their severity varies in a system. Table I suggests appropriate figures of merit for systems differing in these two characteristics. Other system characteristics may suggest other figures of merit.

TABLE I

APPROPRIATE SYSTEM RELIABILITY FIGURES OF MERIT

System Characteristics	Maintenance Permissible	Maintenance Not Permissible
Severity of failures is constant	Per Cent down–time p	Failure rate $\sum_{i=1}^{n} r_i$
Severity of failures varies	Weighted Per Cent down–time $\sum_{i=1}^{n} p_i d_i$	Weighted failure rate $\sum_{i=1}^{n} r_i d_i$

where

p_i is the per cent down–time of the ith item in the system,

r_i is the failure rate of the ith item,

d_i is the degradation in system effectiveness while the ith item is inoperative, as a ratio,

n is the number of items in the system.

The most common systems are perhaps those permitting maintenance and having differing severity of failures. The analysis described below is aimed at this type of system.

BASIC ANALYSIS MODEL

Table II is a format used in the analysis, that also explains the basic operations.

Item = Items which make up the system,

r_i = failure rate of the ith item in per cent per hour,

q_i = the time to restore operation after a failure in ith item,

d_i = the degradation in system effectiveness while the ith item is inoperative, as a ratio,

$r_i q_i d_i$ = a weighted measure of unreliability $p_i d_i$.

TABLE II

BASIC ANALYSIS MODEL

Item	r per cent / hours	q hours	d degradation	rqd per cent degradation
A	1.0	7.5	0.25	1.9
B	7.5	4.0	0.1	3.0
C	1.0	4.0	0.5	2.0
D	2.0	2.5	1.0	5.0
E	3.0	2.0	0.5	3.0
F	7.5	1.0	0.25	1.9
$\sum^{F} r_i q_i d_i$				16.8 per cent

Assuming that $\frac{1}{r_i} >> q_i$, and neglecting scheduled down-time, then $r_i q_i \approx p_i$ = the percent down-time. More sophisticated methods allow p to be determined as a function of random variables.

The heart of this analysis is the assertion that

$$\sum_{i=1}^{h} p_i d_i$$

* Presented at the 1960 Winter Conv. on Military Electronics, Los Angeles, Calif.; February 3-5, 1960.

† Acronutronic, a division of Ford Motor Co., Newport Beach, Calif.

s a useful system reliability figure of merit. This is found y summing the last column of Table II. It weights inividual contributors to percent down-time by the deradation in system effectiveness during that down-time. 'his means that percent down-time-degradation can be onsidered as a measure of unreliability. This provides quantitative reliability figure of merit in terms of ystem effectiveness (or its reciprocal). This can be ery valuable in trade-off analyses, as discussed later.

Fig. 1, is a graphic representation of the analysis esults in Table II. It illustrates the relationship beween percent down-time and degradation in system ffectiveness. It provides more information than just $\sum_{=1}^{h} p_i d_i$, by showing the distribution over p and d.

'he contribution to system unreliability by units A nrough F of Table II can be visualized easily. The nits of percent down-time and degradation in effeciveness are such that the area in the upper right porion represents unreliability. For the example shown $r_i q_i d_i$ = 16.8 percent degradation = system uneliability. Other forms of graphs; e.g., pie charts, ould show the same information.

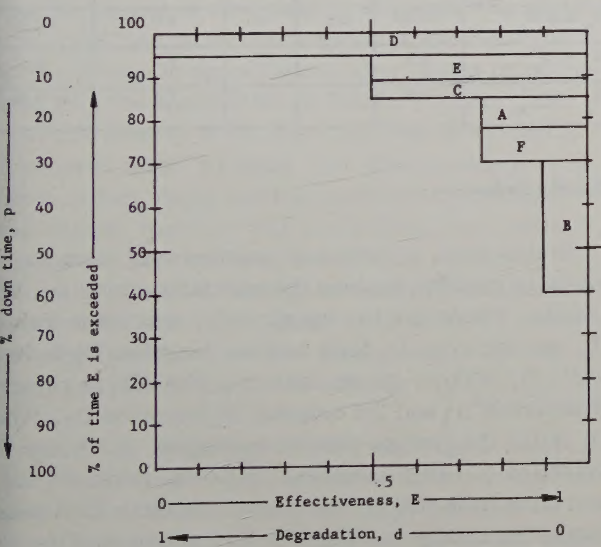

Fig. 1—M Reliability profile

It is interesting that even the widely accepted defini-:ion of reliability is relatively meaningless for this :ype of system. The common definition of reliability s: the probability of a device (system) operating within specified limits for the time and operating condi-:ions specified. Fig. 1 indicates that the probability of everything in the example operating at any given :ime is only 40 percent. However, the above figure of merit indicates the system reliability is 83.2 percent (the complement of the system unreliability or 100-16.8 percent).

After Table II and Fig. 1 have been completed, it is easy to identify problem areas. Those items having the largest rqd contribute the most to system unreliability. They should be carefully examined to see if any reductions can be made in either r, q, or d. With this reliability figure of merit, reducing the time to restore operation, q, is just as valuable as reducing the failure rate, r. This assumes that the maintenance and logistics load is a system parameter independent of system operational reliability. The importance of reducing q supports recent emphasis on built-in failure detection and location features, as well as modules which are easy to replace.

The number of entries in the item column will depend on the extensiveness or thoroughness of the analysis. Many reliability analyses consider failure rates and stresses on individual parts. This analysis can be included by filling out several additional columns and estimating q and d for each part. In some cases, filling items only to the subsystem level may be of value. Entries to the lowest level where failures have differing effects on the overall system effectiveness also makes sense.

Meaningful subtotals may be obtained if items are grouped by subsystem, unit, location, basic function or some other characteristic. Grouping by basic functions allows some isolation of interacting failures.

The degradation in effectiveness, d, is possibly the most difficult quantity to describe numerically. It is almost the same problem as defining numerical measures of system effectiveness, except that this is a relative number, not absolute. d equals one minus the ratio of system effectiveness without an item to the system effectiveness with the item. Thus, absolute system effectiveness does not have to be numerically defined. Of course, some systems have convenient and meaningful numerical measures of effectiveness, such as CEP, number of items manufactured per day, probability of kill, or even just plain profit. It is the author's opinion that the degradation, d, for each possible failure can be best estimated by good judgment, rather than by lengthy system analysis, and that the uncertainties in judgment are less than the uncertainty in other quantities used in reliability analyses.

In estimating the degradation, d, it is well to consider:

Alternate Procedures

Some systems have reasonably good alternate procedures for some failures. A transfer mechanism

on an automated assembly line may fail. An effective alternate procedure may be a temporary manual transfer which will not slow down the line.

Multiple Missions

Some systems have more than one mission. Failures may degrade effectiveness differently for different missions. For instance, a data processing system may be used for payroll, inventory control, and scientific computations. Failure of a payroll check printer would degrade the payroll application, but not the others.

Multiple Modes

Some systems have more than one mode for performing a mission. A bomb-nav system may use radar, IR, optical sensing, or a combination depending on which suits the situation best. Failure of the IR mode may not abort all missions. Also, see 2.

Multiple Channels

Some systems have multiple channels for traffic handling purposes. In a communication system, failure of one channel may only increase the waiting time of low priority messages during peak traffic periods. Failures in nonpeak periods may not degrade performance at all.

Down Time

The relation between q and d is often non linear. Therefore, q should always be considered when estimating d. A sampled data process control system may not drift far from optimum in a few minutes, but within 30 minutes considerable damage may be done.

Human judgment can consider these and other considerations and arrive at estimates quite rapidly. In estimating d it should be remembered that a unit area in the lower right of Fig. 1 represents just as much unreliability as a unit area in the upper right corner.

In cases where rerun or restoration time is necessary after a failure, this time is included in q, the time necessary to restore operation.

REDUNDANCY

Table III and the following discussion suggest procedures for handling four classes of redundancy. Item D from Table II is used as an example in all four classes. The term, c, is introduced to aid in determining the group failure rate (redundant items being down simultaneously). It is the time to restore operation after a group failure or the time to repair D if no other spares are available, as assumed here. To simplify the model, c is assumed to be constant and scheduled down time is neglected. The failure rate for the redundant items is assumed to be the same as for the main item, except that it is assumed to be zero when it is not operating. In each of the four cases a means for approximating the group failure rate is given. Following the four cases, a brief discussion is given on the derivation of more exact relationships.

TABLE III
ANALYSIS FOR REDUNDANT ITEMS

Item	r per cent hours	q hours	c hours	d degradation	rqd per cent degradation
D from Table II	2.0	2.5	2.5	1.0	5.0
D_1	2.0	0.05	2.5	1.0	0.1
D_1 and D'_1	0.1	2.5	–	1.0	0.25
D_2	2.0	0.05	2.5	1.0	0.1
D'_2	2.0	2.5	2.5	0.1	0.5
D_2 and D'_2	0.2	2.5	–	1.0	0.5
D_3 and D'_3	1.33	2.5	–	1.0	3.33
D_4 or D'_4	4.0	0	2.5	1.0	0
D_4 and D'_4	0.2	2.5	–	1.0	0.5

Standby Redundancy

In this case, a redundant nonoperating item D'_1 is ready to rapidly replace the operating item, D_1, when it fails. There are two unreliability entries in Table III: one for when D_1 fails and one for when D'_1 fails while D_1 is down (group failure). When D_1 is repaired, it becomes D'_1 and the original D'_1 becomes D_1. When D_1 fails, the time to restore operation, q, is just the detection and switching time, plus any rerun or restoration time that is necessary. In Table III it is estimated that q= 0.05 hours, or 3 minutes. The group failure rate for this class may be approximated by cr^2, assuming $\frac{1}{r}>>c$.

Priority Standby

This class is the same as above, except that the standby D'_2 is used for a lower priority function until a failure is detected in D_2. The group failure rate for D_2 and D'_2 may be approximated by $2cr^2$ since the standby unit D'_2 does not have zero failure rate and may be down when D_2 fails. The failure rate of the lower priority function performed by D'_2 can be appro

nated by 2r since the function goes down whenever ere is a failure in either D_2 or D'_2.

arallel Operation

This class assumes parallel operation without in- vidual failure detection such that both D_3 and D'_3 must il before the function fails. The group failure rate is en 2/3 r, surprisingly little improvement.

arallel Operation with Failure Detection

This class is the same as parallel operation ex- ept that failures in either D_4 or D'_4 can be detected and orrected without interrupting the operation. The group ilure rate is then the same as in class 2 above and an be approximated by $2cr^2$. This class has an ad- antage over class 2 in not interrupting operation hen a single item fails. This costs one extra set of ilure detection equipment and/or procedures.

act Methods

Exact group failure rates and per cent downtime ay be obtained, subject to the assumptions, through se of the theory of stochastic processes. The analy- s is simplified by the assumption of exponentially stributed repair times, which also seems more re- istic than the assumption of constant repair time.

The life history of an operating item is viewed as "birth and death" process (1). The assumptions of ndom failure rates and exponentially distributed epair times, together with prescribed item charac- ristics and repair discipline, yield a system of fferential equations that describe the operation of e item with time. The equations provide, in parti- ılar, the limiting fractional down-time p $(o \leq p \leq 100)$ the item. For class 3, the solution is $p = \frac{2r(r+u)}{4ru + 2r^2 + 3u^2}$

here u is the reciprocal of the mean repair time,

With this value of p, it is not necessary to approxi- ate p by rq. Thus, the unreliability, pd, may be otained more directly and more exactly. Using simi- r techniques, the exact expectation of the group ilure rate may also be obtained.

It is also possible to obtain solutions as exact as quired by simulation using a radom variable or onte Carlo model (2). The number of runs made termines the accuracy of such solutions.

ASSUMPTIONS AND REFINEMENTS

There are many simplifying assumptions in the asic analysis model above. Refinements in the an- alysis can account for most of the doubtful assump- tions.

Varying Operating Times

The basic analysis assumes that all items are in continuous operation. Where items are in operation for different amounts of time another column can be added to the table to take this into account. This column, b, contains an estimate of the fraction of total system operating time that the particular item is in operation. The percent down-time, p, would then become rqb or the fraction of system operating time that the unit was inoperative. The unreliability is then rqbd.

Variation of d with Mode or Mission

As stated above, d may have different values in different modes or missions. It is possible to use a weighted average for d; averaged over-all modes and weighted by b of each mode. The Σ rqd would be cor- rect, but the reliability profile would be distorted. A better method would enter the item once for each mode, estimating d and b for each mode.

Distributions of q and d

The actual time to restore a function after a failure may vary over a wide range. Using the mean, q, leads to difficulties and distorts the reliability profile. Use of the exponential distribution e^{-qt} is perhaps more correct, but it complicates the analysis considerably.

Also, d may vary with q and with circumstances at the time of failure. If d is assumed to be a random variable with some distribution, Monte Carlo solutions (2) can give the unreliability and the desired relation between distributions of percent down-time and de- gradation.

Scheduled Downtime

The basic analysis assumes that scheduled main- tenance is performed in a manner or at times when system performance is not degraded. When this is not true, the percent down-time, p, becomes rq+s, where s is the percent scheduled down-time. The unreliability is then (rq+s)d. If d is different during scheduled down-time, the unreliability may be rqd_1+sd_2. This can be facilitated in the analysis by adding col- ums for s and d_2.

Overlapping Failures

The basic analysis assumes that failures are independent and that there are no simultaneous down-times of different items. Since there will probably be overlapping down-times, the reliability profile derived from Table II should be tilted slightly in the counter-clockwise direction. Stochastic properties could be introduced to help account for overlapping down-times. Even then, the assumption would probably be made that the degradation from overlapping down-times adds linerarly. There are probably cases where the total degradation would be greater than the sum of the individual d's. However, there are probably more cases where failures in different items interrupt the same functions. Then the total degradation equals the larger of the contributing d's and is lower than the sum of the d's. If this were not true rqd could easily be greater than 1. This effect is probably significant in cases where rqd 25 percent.

TRADE-OFF ANALYSIS

Improved reliability is a primary goal but not the ultimate goal of a reliability analysis. Improved system effectiveness is the ultimate goal where reliability is one of many effectiveness criteria. The above system reliability analysis aids in evaluating trade-offs. It should also point out reliability improvements where trade-offs are not necessary. By rerunning the analysis for different design configurations, comparisons can be made and sensitivities or weak spots can be detected.

The value of adding redundant items and the relative value of several types of redundancy can be easily determined, subject to the assumptions and approximations. Examining the last column in Table III, the improvement in system effectiveness by each of the 4 classes of redundancy is obtained. Note that the contributions from D_1 and (D_1 and D_1') must be added, as must the contributions from D_2 and (D_2 and D_2'). Thus, the unreliability in performing the function for the various cases is:

No Redundancy	0.5 percent
Class 1	0.35 percent
Class 2	0.6 percent
Class 3	3.33 percent
Class 4	0.5 percent

The effect on the reliability profile, Fig. 1, is obvious.

Other reliability trade-offs can also be evaluated. The value of adding failure detection equipment or pro-cedures can be determined. Also, the relationship be-tween decreasing q or r is apparent, although there a other maintenance considerations involved here.

One of the greatest aids in reliability trade-off ana sis is that reliability can be expressed in terms of the common denominator, over-all system effectiveness. Now reliability can be compared with any other parameter whose influence on system effectiveness can be estimated. In many systems reliability may be improved at the expense of weight. Weight can often be related directly to system performance. Another important feature is the improved ability to understand how much money to spend on reliability. Comparisons are then made with respect to the common denominato cost per unit of effectiveness. It is generally desirable to maintain a fairly constant ratio of differential cost to differential performance throughout a system. This can aid in deciding whether to put a given dollar into reliability improvement or other performance improvements.

In any trade-off analysis, the uncertainty in the estimates of r, q, and d must be considered. Generally, trade-off analyses are of most value early in the system design when all these uncertainties are high. Thus, special care must be taken to try and evaluate the influence of all uncertainties.

CONCLUSIONS

1) The above analysis provides a quantitative system reliability figure of merit based on percent down-time weighted by degradation in system effectiveness.

2) The analysis is a simple extension of common failure rate summations.

3) The figure of merit, Σ rqd, allows individual reliability considerations to be intelligently compared with various other trade-off factors.

ACKNOWLEDGEMENT

The writer is grateful to Dr. R. E. Beckwith and B. J. Winter for providing a clearer understanding of the effect of certain assumptions and the use of random variables in this analysis.

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The Reliability of Transistors in Battery Portable Radio Receivers*

ROBERT M. COHEN†

It is estimated that more than ten and one-fourth nillion domestically produced transistorized battery portable radios have been built and placed in operaion in the last five years. By and large, transistor eceivers produced in 1958 had overcome some of the nherent device and circuit limitations present in earlier attempts at transistorized receiver design, and represented a well-engineered and acceptable commercial product. Transistor radios built in 1958 have probably seen about 500 hours service on the average, and some manufacturers have kept fairly accurate and reliable records on field returns; thus, he results should have some statistical significance. For the purpose of this paper, reliability will be discussed in terms of 1) equipment manufacturers' line and incoming-inspection rejects, and 2) field failures n receivers. Admittedly, the first category involves a large number of technical and commercial factors apart from device reliability, but the discussion would not be complete without this consideration and might, n fact, be entirely misleading because of the extremely low field-failure return experienced and the relatively high rate of rejections on incoming inspecion.

INCOMING–INSPECTION AND LINE REJECTS

Fig. 1 shows the percentage of equipment manufacturers' incoming-inspection or in-plant line rejects for transistors shipped from the beginning of 1959 through September 1, 1959. A large percentage f these line rejects are not confirmed on retest and are found to be satisfactory when resubmitted for reexamination, but the gross reject figures shown here have considerable significance in that they at least indicate the degree of application difficulty experienced by the equipment manufacturer. It is interesting to note that, as one might expect, there are more rejects for converter transistors than IF transistors, and that the audio transistors show the least percentage of rejections. Drift transistors used in broadcast-frequency receivers have a lower rejection rate than comparable alloy types operating at the same frequencies in the same applications. It should be noted that almost 50 per cent of the rejects are due to mechanical causes, such as condition of leads or improper or illegible branding, and mismatching, which engineering investigation reveals to be due to handling problems rather than instability of the transistor's characteristic. The information shown in this chart requires further analysis, obviously, and will be discussed in more detail later.

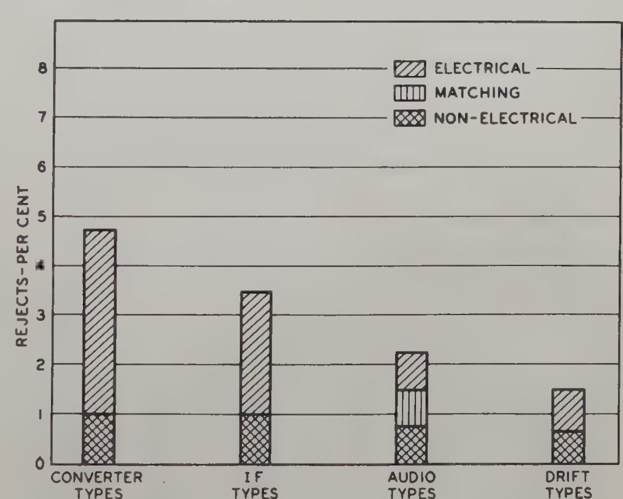


Fig. 1—Line and incoming–inspection total rejects by major type family.

Fig. 2 shows similar information by customer for alloy converter transistors. It is interesting to note that there is wide difference in the amount of rejections for electrical reasons, as well as non-electrical reasons, in this category. The cause of this discrepancy has been investigated and will be discussed subsequently.

Presented at the IRE – EIA Radio fall Meeting, Syracuse, N. Y., November, 1959.
Semiconductor and Materials Div., Radio Corp. of America, Somerville, N. J.

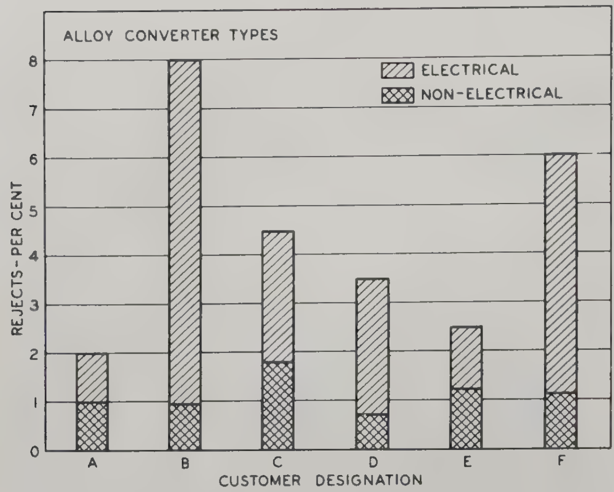


Fig. 2—Line and incoming–inspection rejects of alloy converter transistors by customer.

Fig. 3, which shows similar information for alloy IF-amplifier transistors, indicates about the same situation that exists with converters, although the variation in percentages between customers is somewhat less than with converter types.

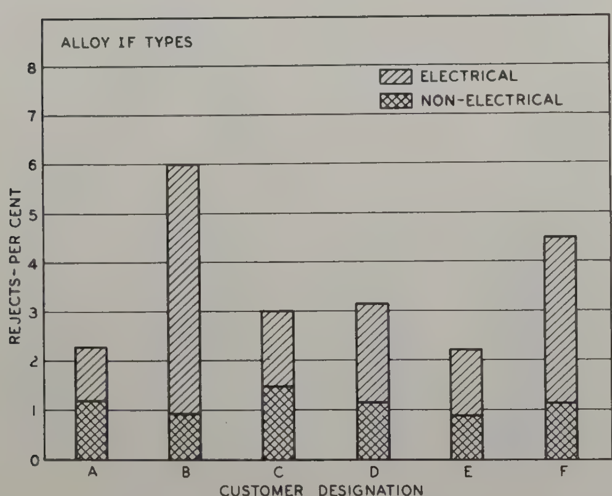


Fig. 3—Line and incoming–inspection rejects of alloy IF–amplifier transistors by customer.

Fig. 4. shows the total return of audio transistors for the same period of time by customer. The level of rejections by customer for electrical characteristics in this family is low, but the amount of rejects for mechanical and non-electrical reasons varies considerably by customer.

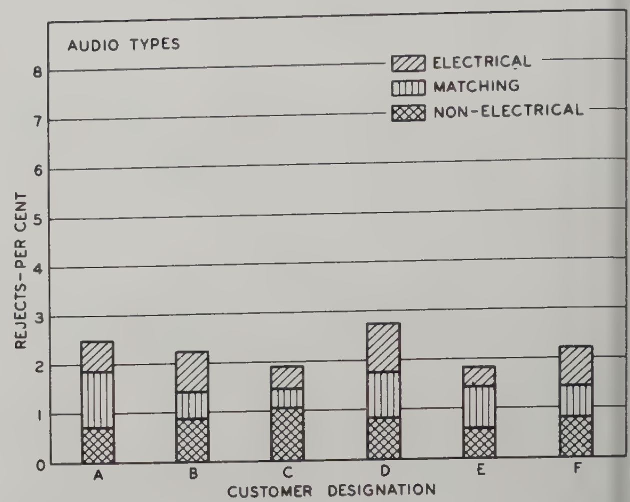


Fig. 4—Line and incoming–inspection rejects of alloy audio transistors by customer.

Fig. 5 shows similar information for drift transistors used as RF amplifiers, converters, and IF amplifiers at broadcast frequencies. The three functions were lumped together so that approximately similar magnitudes could be considered. This summation is possible because there was little difference in the amount of rejection for the three categories of drift transistors. It should be noted that the electrical rejections do not differ widely by customer and are considerably lower than those for the equivalent alloy types shown previously in Fig. 1. The difference in non-electrical rejections is about comparable to that for the audio alloy types.

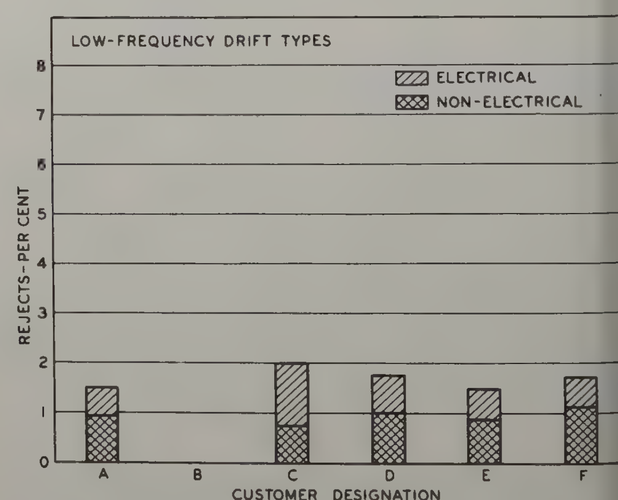


Fig. 5—Line and incoming–inspection rejects of low–frequency drift transistors by customer.

FIELD RETURNS

It has been very difficult to get accurate informa-
ion on the precise magnitude of field rejects because he percentage of rejections has been extremely low. o major or minor complaints have been received in he time mentioned regarding transistor field rejects battery portable radio receivers. Because most anufacturers have some sort of return-privilege uarantee on the transistors in the receivers, it is elieved that any significant problems would have ome to light in no uncertain terms.

Fig. 6 shows an estimate of the amount of field re-
urns experienced in battery portable receivers be-
veen January 1958 and the present time.

Unfortunately, it must be stated that these good esults with low-dissipation types used in battery ortable radios have not been duplicated in the power-
ansistor field, particularly in auto-radio applications. his fact is undoubtedly due to the more hazardous perating conditions involved in this service. Dissi-
ation and voltage transients occurring at high current vels create possibilities for avalanche breakdowns hich do not occur in lower-dissipation applications. he power-transistor situation is rapidly improving, owever, as manufacturers gain knowledge of the de-
ice, and as application pitfalls also become thorough-
understood. Because this paper is concerned only ith battery portable radio applications, further dis-
ussion of this interesting phase of transistor reliabi-
ty will be omitted. Suffice it to say that these results ith battery portable types should not be construed as so being applicable to power types.

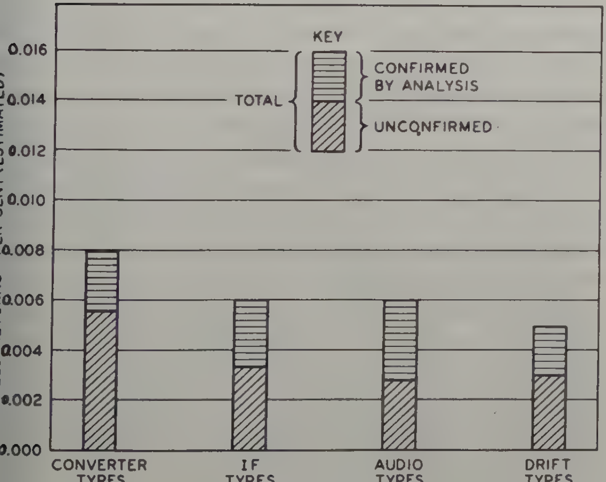


Fig. 6—Estimated field returns since January, 1958.

ANALYSIS OF FIELD RETURNS

It is interesting to analyze the field returns and also to compare the results to manufacturers' life-test experience. The very low field-failure return is better than has been experienced in internal life tests, but there are several good explanations for this discrepancy.

1) Internal life tests are always made at maximum rated conditions and involve extremes in temperatures and humidity cycling. These conditions are considerably more severe than the average environmental conditions.
2) A life-test failure is defined in terms of a variation in an electrical characteristic beyond life-test end-point limits. Field-failure returns are generally limited to the so-called "catastrophic failure" variety. Only a small percentage of life-test rejects fall in this category.
3) A considerable portion of operating-life test failures occur in early hours. A large percentage of the failures which occur on operating life would also occur on shelf life under conditions of moisture and temperature cycling, and in some cases occur merely as a result of elapsed time without excessive temperature or humidity cycling. It is probable that this type of life-test failure is rejected on the equipment manufacturer's incoming-inspection line and never reaches the ultimate customer.

Even so, life-test results indicate, on the average, less than one catastrophic-type failure in 1000 hours per 100 units. In the light of these data, it would seem that the very excellent field experience is not too different from life-test results when all factors are taken into consideration.

Analysis of field returns indicates that the major cause for rejection is mechanical in nature. Poor connections from the internal leads to the emitter and collector "dots" account for more than 50 per cent of the "discernible-cause" category of returns. About 25 per cent of these returns are the result of surface leakage, in most cases due to a defect in the hermetic seal. Applications and service problems seem to be the cause for field returns that result from the transistor having experienced excessive dissipation or having suffered from the effects of excessive heat when it was removed from printed boards.

As transistor manufacturers have become aware of the factors detrimentally affecting reliability, they have endeavored to develop tests and processes which will result in improved product. It has been learned that transistors which exhibit unstable leakage characteristics, even though they may be well within manu-

facturing limits, can be potentially dangerous. Consequently, automatic "creep" indicators have been developed which more accurately fore tell when processing must be improved to obtain better surface conditions. Improvements in surface treatment which yield cleaner and more stable surfaces have been developed with great improvement in reliability. Mechanical problems involving poor connections have been investigated by the use of thermal shock in combination with noise tests, and the internal leads have been redesigned to present a larger surface for electrical bonding. Typical examples of the manufacturing improvements that the industry is employing to achieve improved reliability include accurate inspection and control of welding equipment to avoid burned welds or cold welds, and improved detergent "pressure bomb" testing equipment used at more frequent intervals to indicate the presence of leakers so that immediate corrective action can be taken.

ANALYSIS OF LINE AND INCOMING – INSPECTION REJECTS

Analysis of the line and incoming-inspection rejects shown in Figs. 1-5 indicates that these statistics are influenced at least as much by equipment design as they are by the inherent properties of the transistor and/or the manufacturing variations which may be involved. Discussion of these results with engineers in the RCA Applications Lab. developed the following information which may be useful.

Most failures of converter and IF-amplifier transistors seem to occur in instances where the receiver was originally designed around one manufacturer's type number and subsequently produced with another manufacturer's transistor of the same type number or a different type number having similar characteristics. It is obvious from this analysis that transistors of different manufacture having the same type number are not, in reality, interchangeable in all respects despite the fact that they may appear to be the same based on their ability to meet a limited number of published specifications. This is a problem which transistor manufacturers must resolve in EIA activities, and it certainly needs and deserves major emphasis. Most transistor manufacturers have been made keenly aware of this situation and are now working energetically on corrective measures. In this regard, it seems that it should be the responsibility of the manufacturer initiating the type to specify its characteristics so thoroughly that there can be little left to the imagination regarding its electrical parameters. It then becomes the responsibility of the manufacturer copying the type to duplicate these electrical characteristics, and the mechanical characteristics as well, closely and carefully. The industry has been guilty of negligence in this regard, but circumstances should improve as the situation begins to stabilize.

Converter Transistors

As shown in Fig. 2, the wide variation in rejection rate for converter transistors made on the same line in the same period of time indicates beyond doubt that converter circuit design plays a dominate role in the results. It seems impossible to over-emphasize the need for adequate and proper consideration of the normal variation in converter transistors during design of the converter circuit. It is most advisable to follow a procedure in design of the converter coil which consists of carefully following the transistor manufacturer's recommendations, then obtaining low- and high-limit samples, and finally obtaining satisfactory results with these samples before concluding that the converter design is satisfactory. Problems have arisen as a result of the choice of incorrect dc operating points or dc stability factors in the biasing networks, improper magnitude of oscillator-injection voltage or developed oscillator bias, and the use of coils having Q'S which are too low or which vary rapidly with frequency.

If Transistors

The statistical information shown in Fig. 3 leads to a similar conclusion for IF-amplifier transistors. As might be expected, however, the situation is a little less severe, probably because operation in a multifunction stage such as a converter accentuates variations between transistors. The major problem with IF-amplifier system stems from a failure on the part of the receiver designer to give due consideration to stability and interchangeability design criteria. Generally speaking, when IF systems of these receivers are designed with a more or less empirical approach, trouble inevitably results. There is a tendency to use too high a tuned impedance on the average and then insert losses and reduce the impedance of one of the stages to a point where stability is obtained. Thus, less-than-optimum results regarding stability and interchangeability are achieved. The IF-amplifier system should be designed, not empirically developed.

With regard to the IF-system design, mention must be made of automatic gain control agc considerations. The designer must recognize that good interchangeability requires a somewhat degenerative dc circuit for each transistor, where as high agc sensitivity requires just the opposite condition. A proper compromise must be devised between the desired agc figure of merit and interchangeability. Otherwise, the transistor manu-

acturer may be requested to supply selected transis-ors to very narrow dc beta ranges. This procedure is costly whether or not the costs are transferred direct-y or indirectly to the user.

Drift Transistors

The much lower rejection rates experienced with drift transistors, as compared to alloy units, relates in a very direct way to the IF-transformer design considerations discussed above. Fig. 7 shows the circuit impedances and transistor impedances in the converter and if systems of receivers using alloy transistors and drift transistors. It should be noted that the very high output impedance of the drift transistor permits considerable variation between transistors for this characteristic without noticeable effect on the circuit performance. It is believed that this situation, more than any other single factor, contributes to the excellent results with the drift units.

FUNCTION	ALLOY TYPES			DRIFT TYPES		
	Rout (OHMS x 10^3)	Normal Load Impedance (OHMS x 10^3)	Loading Factor	Rout (OHMS x 10^3)	Normal Load Impedance (OHMS x 10^3)	Loading Factor
Converter	70	70	1	300	15	20
First if	70	7	10	770	15	51.3
Second if	30	5	6	475	9	52.8

Fig. 7 – Comparison of circuit impedances and transistor impedances in the converter and if systems of receivers using alloy transistors and drift transistors.

THE EFFECT OF SUPPLY VOLTAGE ON REJECTION RATE

Transistors of the same type and date of manufacture are used in many different receivers, some of which operate at 4.5 volts, others at 6 volts, others at 9 volts, and a few at 12 volts. Although it might be expected, particularly with audio units, that there would be more rejections in receivers using the higher voltage, this was not the case. There seems to be little correlation between the receiver battery voltage and the rejection percentages. In most receivers, the IF and converters systems include filtering resistances which reduce the voltage across the transistor. Also, in the case of the output stage, the peak current requirements demanded with lower supply voltages probably cause as much trouble as the breakdown characteristics requirements imposed with higher voltage supplies. In any event, analysis of these data does not indicate any reason for recommending a particular supply voltage between 4.5 to 12 volts within the transistor ratings to improve reliability.

ALL-WAVE RECEIVERS

Fig. 8 shows the accumulative rejection rates on drift transistors used in the tuner and if system of all-wave receivers. The oscillator transistor has appreciably more electrical rejections than the other types. These failures have been analyzed to be due primarily to a special problem involving frequency shift with supply voltage. Thus, there is a circuit as well as a device problem. The RF-amplifier transistor has a higher failure rate than the mixer because of the necessity for maintaining excellent noise characteristics and the more critical nature of the RF-amplifier with regard to its effect on this receiver characteristic. Surface leakage seems to have a dominant influence on noise performance in this type of application, although there is ample evidence to indicate that imperfections in the transistor such as "unwet" areas of the junction or excessive etching (which produces high r_{bb}' or reduces emitter-injection efficiency) are also important factors causing noise.

It is interesting to note how drastically the rejection rates have been reduced with time as a result of the solution of circuit problems and test-set correlation problems. There was practically no change in the device or processing during this period. Correlation problems on test sets, particularly those used for incoming inspection in receiver manufacturing plants, must be given serious consideration in the rejection rates for transistors in all-wave receivers. Also, the maintenance of accurately controlled temperatures in the incoming inspection test areas is essential if accurate and repeatable results

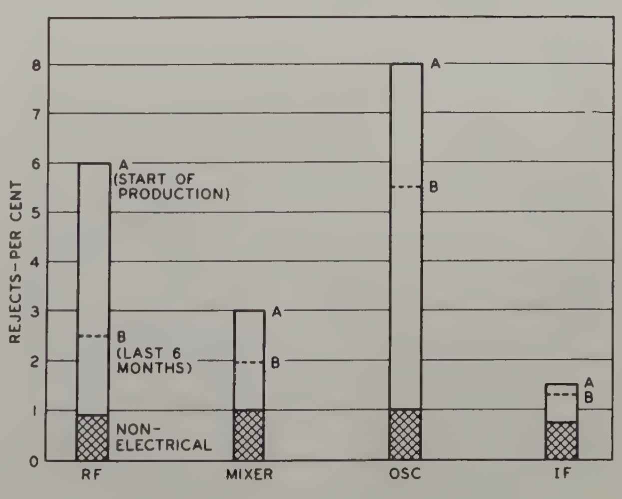


Fig. 8 — Accumulative rejection rates for drift transistors used in the tuner and IF system of all-wave receivers.

are to be obtained. Attempts to develop conversion factors for variation in transistor characteristics as a function of temperature, and thus eliminate the need for accurate temperature control, have been singularly unsuccessful. There is no effective substitute for the maintenance of proper temperature at the test position if repeatable results are to be obtained on static or dynamic characteristic measurements.

It is also interesting to observe the very low rejection rate for drift transistors used in the IF-amplifier stage of the receiver as compared to the much higher rates for the "front-end" transistors. Again, the circuit complexity is the dominant factor influencing the over-all result. As transistors are used at frequencies approaching the limits of their capabilities, much higher rejection rates are likely to occur because the circuits become less tolerant of transistor variations.

CONCLUSIONS

Although the average field-failure rates of less than one hundredth of a per cent per 1000 hours for transistors in battery portable radios is gratifyingly low, the two-to-five per cent rejection rate on incoming inspection or on the equipment manufacturer's production line is still far from the desired level. Many aspects of this problem will require the continued mutual efforts of transistor manufacturers and equipment manufacturers to effect better standardization and interchangeability through EIA functions. The importance of the closest possible cooperation between the application engineer and the equipment designer, particularly in the design of converter and if circuits and in the establishment of proper incoming inspection and line test procedures, cannot be overemphasized. Despite these problems, it is clearly evident that the transistorization of battery portable receivers has resulted in a new and dramatically improved level of product reliability.

Automation for Quality Control Testing of Electron Tubes

ROY A. MCNAUGHTON, † *MEMBER, IRE*

SUMMARY— Prior to the mid Forties most electron tubes were production—and quality-tested on an attributes (go-no-go) basis only. Quality-sample sizes were moderate and statistical paper work was at a minimum. Since that time quality-control testing has increased by leaps and bounds under the pressure for high reliability, performance, and uniformity. These factors have increased the quality-control work load to the point where an appreciable portion of the tube manufacturing cost is involved in the quality-control testing and statistical evaluation procedures.

In an effort to hold down the rapidly mounting costs of quality testing and data evaluation, to improve operator accuracy, and to reduce the number of tests, a test set has been developed which performs many of the tests automatically. The set provides digital data output for each test on each tube in punched tape, reads out the tape, and prints a copy of the punched data. The punched tape is then fed to a computer which analyzes the data for the entire sample and prints out the answers for those statistical factors such as lot means, standard deviations, per cent deltas, etc., required for the attributes-variables acceptance criteria for lot acceptance. The test set is designed to perform those static and dynamic tests normally performed on a Vacuum-Tube-Bridge test console. It has twenty test positions and will measure and record ten different characteristics on dual section tubes. Provisions are included for manually feeding test data from other equipments into the punched tape for analysis by the computer as desired.

The use of precision components and test circuitry has provided a high-accuracy, one-operator test set capable of supplanting four or five manually operated test sets and of reducing the time lag and labor force required for statistical reduction of the test data obtained.

† Receiving Tube Operations, Sylvania Electric Products, Inc., Emporium, Pa.

INTRODUCTION

Prior to the mid-forties most electron tubes were used for home entertainment and land-mobile applications. Some aircraft industrial and miscellaneous applications existed but these were definitely in the minority.

Through this period practically all production and quality-control testing was strictly on an attributes (go-no-go) basis with statistical computations and paper work at a minimum. Samples for quality acceptance testing were moderate-to-large in size but, in general, required only one handling for test purposes. The tests performed were simple by today's standards and consisted mainly of the normal static current measurements, transconductance, gain or power output, noise and shorts, and continuity.

BACKGROUND OR STATEMENT OF PROBLEM

Fig. 1 is a table summarizing the specification for two tube types, the prototype 6AK5 and the reliabilized version into which it evolved as type 5654/6AK5W/6096. The left portion of the table is typical of type 6AK5 requirements as of August, 1944. This specification contained the following tests for production, quality, and design control of outgoing quality: carton drop; vibration; heater current; heater-cathode insulation; grid current; plate current, plate current cut-off, screen current, transconductance (normal EF); transconductance (reduced EF); repeat of plate current and transconductance tests after 10 minutes operation in a special grid drive circuit; RF noise; capacitances; and one static life to 500 hours with filament, grid and heater-cathode currents and transconductance end point limits.

COMPARISON OF SPEC. REQUIREMENTS		
TESTS	Comm'l 6AK5	MIL 5654
Standard	12	13
Special	2	4
Life	1	3
Statistical	2	18
Total	17	38

Fig. 1.

Of these tests, six were 100 per cent production tests, nine were design-sample tests, and two were performed after a 24-hour holding period.

It may be noted that this spec contains only two delta tests with percent difference limits requiring statistical computation.

Following the mid-forties, statistical quality-control techniques involving AQL's sampling plans, and variables control came to the forefront.

Accompanying the growth of statistical control, there evolved many new applications for tubes such as TV, missiles, computers, etc., which demanded more stringent control of normal characteristics and added many environmental and special life tests with per cent difference limits between before-and-after testing.

The new quality-control technique, in general, reduced the sample size required for each group of tests, but the added tests and environmental requirements resulting from the more stringent control and the new applications have more than compensated for the reduction in sample size. In addition, the amount of statistical computation, record keeping and clerical work involved has increased tremendously.

The right-hand portion of Fig. 1 shows the current spec summary for the type 5654/6AK5W/6096 which is the present MIL version of the type 6AK5.

This summary reflects the impact of statistical control and environmental testing on the quality-control processes. Additional tests, not requisite in the 6AK5 specification, include shock and fatigue vibration with post test limits on vibration, heater-cathode leakage, transconductance and grid current; glass strain; intermediate-cut-off-bias plate current; high-filament-voltage grid current; stability life with a per cent delta transconductance limit; survival rate life; heater-cycle life test with inoperatives and heater-cathode leakage end points; and an extension of intermittent life to 1000 hours giving at least one more reading period. Additional computations include lot averages for each normal test characteristic; per cent change-in-transconductance-over-time for the stability life test end point; per cent change-in-transconductance-over-time at both normal and reduced filament voltage for the 500-hour intermittent life end points; and combination of various test rejects for group AQL conformance.

These additions to the quality-control work load have resulted in the addition of statisticians, clerks and typists to the personnel of the quality sections, an increase in the number of test sets and operators and an increase in the number of life-test sockets to accommodate the life requirements.

DESIGN – DEVELOPMENT OF THE SET

In an effort to discover ways and means for curtailing the increasing cost of testing and the time-lag required for lot release, the entire quality control process was reviewed to determine where automation could produce the desired results.

Since many of the measurements contributing to the increased cost and time lag are made on the vacuum-tube-bridge test sets, and these measurements provide the data for the statistical work, it was concluded that automation of the bridge measurements and statistical computations would provide the best possibility for cost reduction.

Subsequently, the design and development was undertaken of an automatic test set which would perform those tests normally made on the vacuum-tube-bridge console and record the data in a form suitable for automatic computation.

Many problems were encountered during the design and construction of the test set which required the cooperative efforts of the equipment designers, industrial engineers, statisticians and communications engineers. An example of these problems was the setting up of the sequence of tests which could be performed by the test set in such a manner that the data from a multitude of tube types could be run through the computer by use of a minimum number of computer program instructions.

The final design of the test set has provisions for preheating, performing twenty tests in one cycle, automatic read-out to punched tape, automatic tape read-out for verification of equipment functioning and provision of a printed copy of the test data, an automatic serial number system to identify individual tube test data, and those coding symbols required for proper programming of the data into the computer.

The twenty test positions provide the necessary steps for making the following tests on dual-section tubes: filament, plate, screen-grid, control-grid, and heater-cathode-leakage currents under dc conditions; dc or ac emission; transconductance; plate resistance; and intermediate and cut-off-bias plate currents. In addition, power output and/or ac amplification tests may be substituted into the test cycle as required by deletion of other tests.

To facilitate data processing, the tests are sequenced so that those having values normally distributed occur at fixed steps in the test cycle. Any test may be omitted from the test sequence by wiring in a skip function on the program board. Tests at a changed heater voltage condition such as reduced-heater plate current, transconductance or power output and high-filament grid current are made by first testing the tubes at normal conditions and then rerunning them in the same order under the changed condition and with all tests except those desired skipped out. The two-panel preheat system provides adequate time for stabilization under the changed heater power condition.

At this point, a brief general description of the test set will aid in following the more detailed explanation of its parts and operation later in the paper.

DETAIL DESCRIPTION

The over-all set (Fig. 2) is housed in three separate cabinets with interconnecting cables to permit freedom of location in the test area. The first cabinet, Fig. 3, usually located to the left of the installation, houses a group of power supplies and a 400-cycle signal generator. Sufficient programmable, regulated dc supplies are provided to permit presetting of all required test voltages. Through the switching system the voltages for a given test are picked up as required and fed to the tube under test.

Fig. 2.

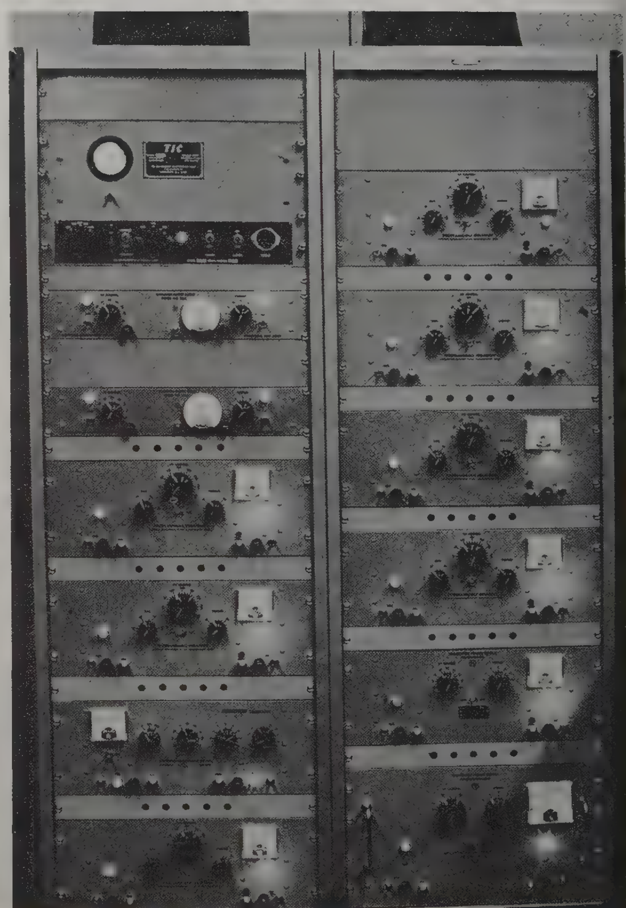


Fig. 3.

Presetting of the supplies was adopted to eliminate the time lag and drift in voltages usually encountered in changing the output from a regulator and thus to speed up the balance time of the indicator system.

The 400-cycle generator supplies the test signal voltages and the power for a servosystem used in the plate-resistance test.

The second cabinet,shown in Fig. 4 houses the preheater, test sockets, program board, switch network, a dc preamplifier, a dc digital voltmeter, an ac-to-dc converter and a second digital voltmeter, two memory matrices, function control switches, an automatic serial number generator, a scanning switch, a diode coding matrix, circuit components for transconductance, plate resistance, power output and ac emission tests, and various power supplies for the switches and preheat panels.

This section is the heart of the entire unit and controls the entire test system.

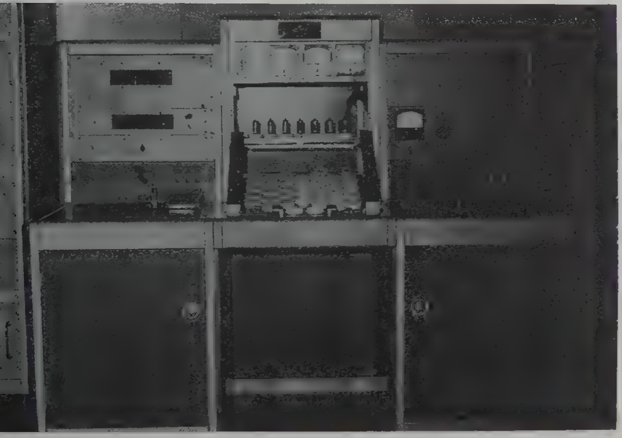


Fig. 4.

Fig. 5 shows the third cabinet, which houses the tape punch and transmitter and acts as the pedestal for the printer and a keyboard.

The transmitter and printer read the tape after it is punched and a copy of the data is printed. This was set up in this manner to enable the operator to detect troubles in the read-out section of the system and allow quick scanning of the data for obvious set malfunctions.

The keyboard is used for manual insertion of identification data in digital form into the punched tape. It also may be used to insert coding for making corrections to data or for preparing tapes from data obtained from other sources.

All of the operating controls are located near the test sockets for operator convenience. The number of plug boards and adjustments to be changed when the type under test changes have been kept to a minimum to reduce lost time in making a change-over from one type to another. The maximum time for a change exclusive of loading the preheat panels and inserting the required identification data into the tape is under three minutes.

With this general description as background, the detailed account of the operations and automatic features of the set should not be too difficult to follow.

Fig. 5.

The operator places the proper preheat socket panels in the set, Fig. 6, adjusts the filament voltage tap switches and variacs located on the right panel, Fig. 7, and then loads the preheat panels with tubes.

Next she places the proper card in the static card reader, shown in Fig. 8, which sets all the required dc test voltages through relay operations on the programmable regulated power supplies. If required, the test socket adapter, which is visible in Fig. 5, is replaced by one of the required type and the proper prewired program board is inserted in the AMP patch-board holder, Fig. 9. The socket adapter is changed only with a change in the tube base type, for example T5 1/2 to T6 1/2, etc. The program board carries all sampling resistors for dc measurements,

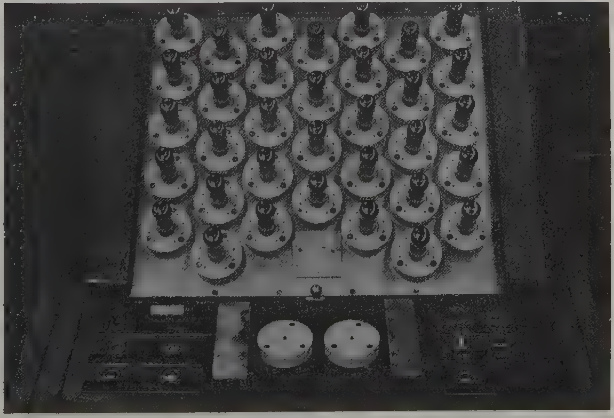


Fig. 6.

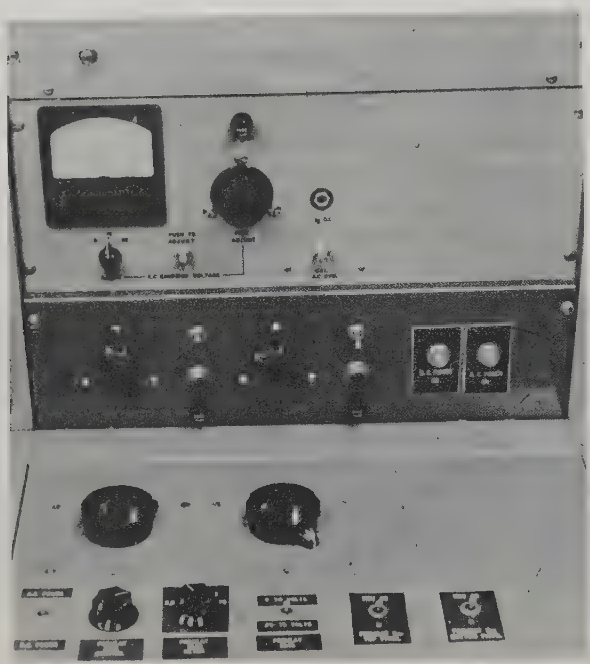


Fig. 7.

Fig. 8.

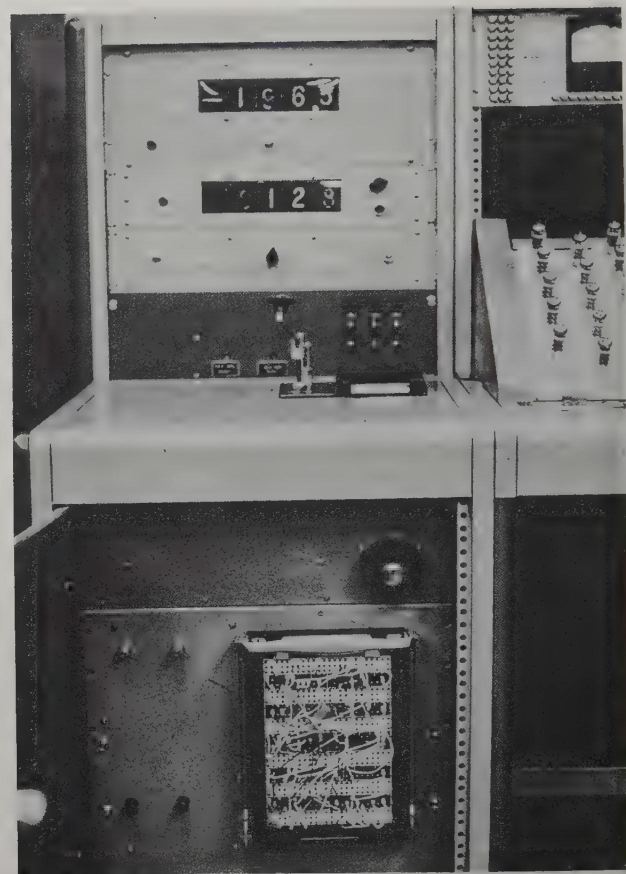


Fig. 9.

and provides terminal points for selection of voltages for each test, a control point for selection of the dc or ac digital meter for each test, a control point for skipping a test, test signal terminals, and output signal connections.

Following these changes the operator types out the type number, lot number, test number and any other identification coding on the keyboard which places this information into the tape. After this she sets the serial number unit to 001 and is now ready to start testing tubes. By this time the tubes on the preheater have had sufficient time to stabilize and testing may begin. Tubes from the preheater are placed in the two test sockets, seen in Fig. 6. Socket 1 is under test conditions while socket 2 remains on preheat until all testing on socket 1 is complete.

The operator presses the "start" button and from this point all testing is automatic as long as the test sockets are kept filled with new tubes or until the complete sample has been tested.

Pressing the start activates a scanning switch which picks up carriage return and line feed symbols and scans the serial number unit thus causing the symbols for CR, LF and the number 001 to be punched

into the tape. On the last step this switch causes the test selection switch bank, Fig. 10, to advance to the first test position. In this position, only heater voltage is applied to the tube under test and the dc meter is connected across the filament current sampling resistor. By virtue of a read-out-at-balance feature the digital voltmeter balances and feeds the digital value of filament current into the memory matrix.

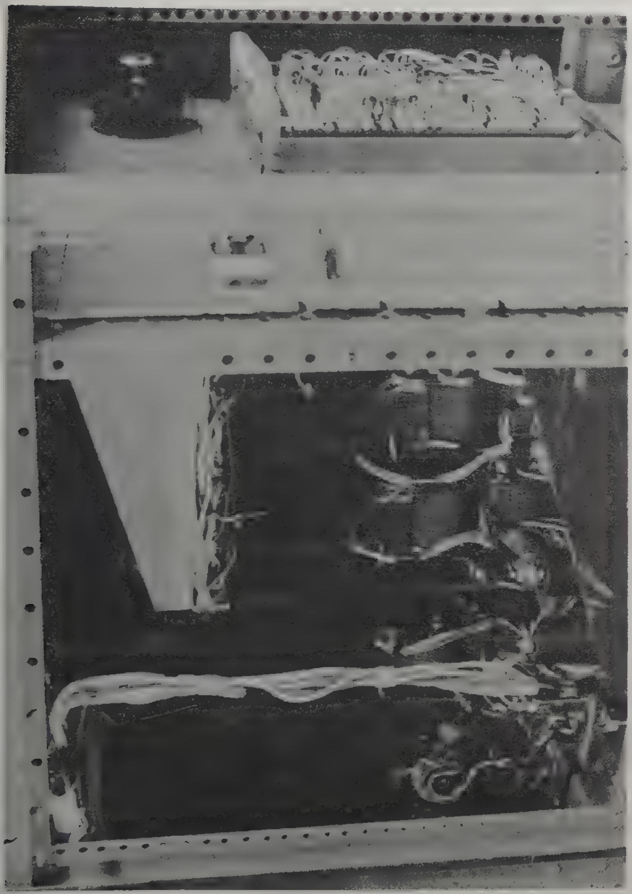


Fig. 10.

This reading is held in memory until read-out by the memory scanning switch which feeds the value through the diode coding matrix into the tape punch, shown in Fig. 11. As soon as the value of filament current is scanned, a control signal unlocks the memory matrix and digital voltmeter and advances the test selection switches to position 2, the plate current test section 1. As soon as the stepping switches advance to position 2, the proper voltages, sampling resistor, tube terminations and digital voltmeter connections are set-up through the program board and the digital meter starts to balance. When it reaches balance, the value of plate current is locked in memory and proceeds as described for filament current.

After all tests on tube 1 have been completed, a stop symbol is fed into the tape, the serial number unit advances one digit, testing switches to test socket 2 while socket 1 returns to preheat conditions, and the serial number scanning switch goes into operation picking up carriage return, line feed and serial 002.

As soon as testing on tube 1 is completed, this tube may be removed and tube 3 inserted in its place.

This procedure continues with testing alternating between sockets 1 and 2 until all tubes in the sample have been tested. Should the operator fail to remove and replace a tube in one socket before testing is completed on the other socket, the test cycle automatically stops. Likewise, if a socket remains empty the cycle stops. In either case the start button must be pushed to continue testing if desired.

If one or more changed heater voltage tests are required and the sample size is such that the two preheat panels (70-tube capacity) will accommodate all the tubes it is possible to return the tubes directly to the preheat panel after completing normal voltage tests. Then as soon as one panel of tubes have all been tested, that panel may have the heater voltage changed and be preheating under the new conditions while the other panel of tubes is being tested. This

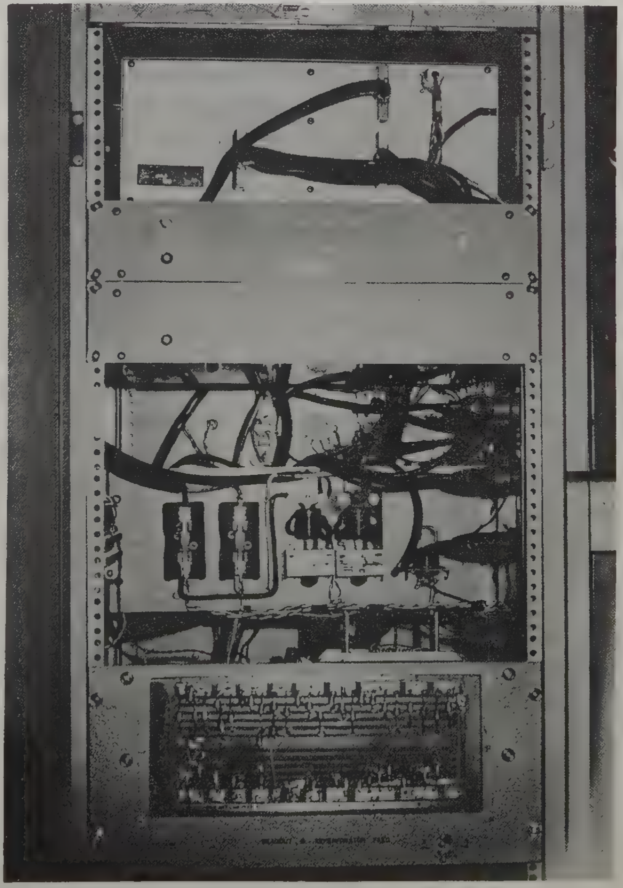


Fig. 11.

increases the stabilization time on the tubes and decreases the lost time between normal and changed EF testing.

The control section of this set contains many other provisions of most importance to the proper timing and flow of information through the system which will not be explained here. Several operating provisions are included which may be of interest. A manual-automatic switch is provided which, when in the manual position, deactivates all the automatic test-cycling circuits and permits manual indexing through the test cycle by pressing the index switch for each test. The read, scan and punch functions remain automatic.

A switch is provided to "hold" the serial number generator and thereby maintain the same tube number when it is desired to repeat-test a tube before proceeding to the next tube. This is accomplished by pressing the appropriate repeat-test switch.

One control function of interest is the provision for a forced read-out. Should a test value be sufficiently variable that the digital voltmeter fails to balance within a preset time interval, a circuit is activated which forces a readout. Since the value on the digital voltmeter at the instant of forced read-out is of absolutely no value, it is not recorded and in its place the symbols 00X are punched in the tape. This is a coding signal for the computer to delete all measurements for this tube. Should a set malfunction be suspected of causing the forced read-out, the tube may be retested at the end of the sample.

DATA PRESENTATION

In the foregoing description various references were made to such symbols punched in the tape as "carriage return," "line feed," "stop," etc. "Carriage return" and "line feed" are used in conjunction with the printer to place the results of tests on each tube on a separate line on the printed copy. The "stop" symbol is used by the computer to denote the end of tests on each tube and is used also in conjunction with the forced read-out symbol "00X" to limit the data to be eliminated from the accumulators.

By proper arrangement of the test sequence, data reduction procedure, and computer programming, it has been necessary to prepare only three computer programs in order to handle the great majority of tube types.

These include one program for the single triodes, diode-triodes, amplifier pentodes and diode-pentodes; one for the dual triodes, triode-pentodes and duo-pentodes; and one for the power triodes and pentodes and several special purpose types.

Computations made by the computer include sample averages and standard deviations for all normally distributed characteristics; calculation of amplification factor, when required, from the GM and RP readings for each tube; per cent deltas with change of filament voltage or over time; and the number of rejects for each characteristic. These calculation results are all printed out for immediate use.

By use of a separate computer whose speed of operation exceeds that of the test set by a good factor, it is possible to use it for other projects adaptable to computer operation and thereby to obtain full utilization of this part of the system.

At present the testing speed of the automatic recording test set is equivalent to approximately five manually operated vacuum-tube-bridge test sets. In future models it is believed possible to achieve an appreciable increase in the speed of operation by the use of more modern digital meters and some changes in the control circuitry of the set.

Over-all accuracy is within 1 per cent for dc measurements and within 2 per cent for ac.

CONCLUSION

In conclusion, the development of the automatic recording test set has provided a means for accumulating the vast amounts of test data for electron tubes demanded by current quality control techniques in shorter time, at less cost, at better accuracy, and at a reduction in the demands on the test set operator whose prime requirement has been reduced to one of mechanical dexterity. Also, it has provided the means for obtaining a great amount of additional information about tube quality past and present at the cost of a slight increase in testing and computer time.

It is definitely a major step toward automation of the test function in the manufacture of electron tubes and an assist in holding or reducing testing costs in spite of the ever increasing demand for more testing and statistical computations on the test data.

Aspects of Reliability in Transistorized Home Radios

JOHN J. CORNING † ASSOCIATE IRE

INTRODUCTION

In this day and age, the concern for military prowess and the conquest of space are the more publicized areas where sound engineering and reliability are needed. More than likely, the average citizen-taxpayer does not fully understand the term "reliability." Yet the fact that something malfunctions such that the launched rocket falls into the sea is sufficient indication that the operation of the device was not as intended. Oddly enough, an average person might, in fact, be more irate at the malfunctioning of a $35 transistor portable radio than the malfunction of a billion dollar space rocket at launching. Those who design transistor radios have no less an obligation to design a reliable product than those who strive for space rocketry.

What, in fact, does the term reliability mean as applied to a transistorized home radio? We might define reliability as "sustained high quality performance." We imply a product, which, from its initial design and assembly phases, has high quality built in. That is, each and every radio of the same design has uniform and closely controlled performance criteria. We further imply that this initial high quality performance remains unchanging for a long period of time. It is the purpose of this paper to discuss:

1) some occurrences which would constitute poor reliability,
2) considerations whereby high quality and reliable radios can be designed,
3) efforts whereby transistors in particular are screened for quality attributes.

ACHIEVING RELIABILITY

In general, all problems causing poor reliability can conveniently be classified into two categories, 1) catastrophic defects, causing the set to play not at all, and 2) defects contributing to gradual performance change towards either weak or oscillatory extremes. Some of the contributors to the catastrophic category are

† Transistor Application Dept., General Electric Co., Utica, N.Y.

1) open wiring,
2) open components,
3) shorted components,
4) board breakage due to dropping,
5) other mechanical failures.

The matters relating to performance drift are somewhat more complicated.

Some of the contributing factors are

1) change in transistor parameter values with time,
2) change in capacitor or coil attributes with time,
3) battery changes,
4) heat and humidity effects.

If these many factors which cause catastrophic failures or performance change are known, how might they be avoided to attain a high quality, reliable radio? Our answers will be given with particular emphasis on the transistor.

Without doubt, the most significant asset a designer of transistor circuits might possess is that of complete understanding of how a transistor functions. In particular the knowledge of what a transistor is would reveal precisely what it is not. Awareness of three classes of information is the means towards a high quality, reliable design.

The first deals with the maximum voltage and temperature ratings of the device. The second is the fact that mass production quantities of transistors necessarily implies a distribution on the values of the various significant parameters. The third relates to the test procedures whereby transistors with latent detects are screened from use.

The maximum junction temperature is established by the transistor manufacturer. Its value is typically established as a function of the maximum temperature experienced by the transistor during manufacture minus some safety factor. Most manufacturers employ high temperature ($90^{\circ}C$ - $110^{\circ}C$) stabilizing bakes either before or after encapsulation. If, after encapsulation, the junction temperature becomes greater than that of the in-process stabilization, moisture or other impurities might be surrendered and confined within the case. These would only serve to contribute undesirable surface phenomena. Every transistor has a fixed thermal resistance. This attribute relates to

the construction of the device and its ability to conduct heat from the junction to the case. Practically speaking, the thermal resistance means that a transistor can dissipate (depending on ambient conditions) a specific power before the junction temperature rating is exceeded. Heat sinks may be employed to enhance the heat radiating ability of the transistor. Sinks thus enable a transistor to dissipate added power before reaching the junction temperature limit. Maximum junction temperature, thermal resistance and maximum power dissipation are thus related attributes. A basic characteristic of a "reliable" circuit is that the transistor, under the severest power and ambient conditions anticipated, is within the junction temperature rating.

Consider the voltage limitations. The three major breakdown voltages, avalanche, h_{21b} equal unity, and punch-through, are described in the literature. Most important in radio work is the h_{21b} equal unity or h_{21e} equal to infinity rating. There are, of course, modifications of the voltage value of this phenomenon due to emitter-base circuit resistance value. If the breakdown voltage value is exceeded, the result will be excessive and possibly uncontrolled I_c and potential damage to the device. For the sake of reliability, a transistor in its associated circuit must never experience an instantaneous voltage greater than the applicable breakdown rating.

The matter of parameter distributions can easily be the undoing of a circuit thought to be perfect. For most devices, such static matters as leakage and forward current gain are controlled. Such dynamic matters as IF power gain, conversion gain, or IF current gain have their respective controls also. Specifying the parameter limits does not of itself assure trouble-free transistor usage or uniform circuit performance. Consider an audio unit which has controls on h_{FE}, h_{ib} and leakages. The h_{ib} parameter is in the denominator of audio power gain expression. For point of illustration, assume the transistor specification has a maximum h_{ib} value of 6 ohms. The transistor samples used in the circuit design might all have had h_{ib} values in the order of 4 ohms. Conceivably, subsequent lots of transistors might have h_{ib} values to the accepted 6-ohm limit without any significant level change in current gain. The circuit gain would certainly vary. Thus the basic concept of quality is lacking. An inadequate design program similar to this example cannot exist in the design of a high quality product. Realistic and meaningful parameter controls must be specified, and complete exploration of the same must be made if high quality and reliability attributes are to prevail.

The preceeding matters, when properly considered, assure that high quality performance be attained and maintained. We must now consider the means whereby transistors are evaluated to avoid using those with poor reliability attributes, generally, 1) defective mechanical structure, 2) surface contamination and 3) bad case seals. A number of test procedures allow the evaluation of these matters.

Before engineering approval is given at the Radio Receiver Department, each new transistor type is subjected to 85° C storage life tests and thermal cycle testing between -30° and +75° C. Leakage stability with voltage is studied. Level instability, if any, would suggest an undesirable surface condition. Dew point studies are also made for protection against moisture contamination. If the life test behaviors are satisfactory for a minimum of 500 hours, and if the other studies give acceptable results, the type is approved. Thereafter though, samples are taken from each production lot and life tests are begun. In this way, case histories for individual types are established. Product inconsistencies, if any, are usually observed within the first 100 hours of life and remedial action taken. All production lots of transistors are further required to pass incoming inspection testing after a thermal cycling. The sample must pass the AQL controls imposed for the various parameters. Prior to leakage testing, each unit is preaged for a minimum of one minute. Collector to base voltage is applied with the emitter open. After the preaging, the leakage test is made. The stability of the leakage level is observed for 15 seconds. Drift or creep of leakage is a reject. At the present time, the dew point check is not performed on all samples. The one matter difficult to cope with is that of defective mechanical structure. This is typically a poor fusing of tabs to dots for alloy types. Engineering studies now being made reveal that if a transistor with a defective structure is operated during thermal cycling, intermittment operation is observed. Should continued investigation of this matter confirm the early findings, catastrophic field effects due to mechanical weaknesses will be drastically reduced.

These endeavors are constantly evaluated for possible improvement. Units which will open, or assume tremendous leakage levels due to contamination are the undoing of a circuit, even if it is designed for high quality and reliability. Units which are out of specification, or possess latent catastrophic defects must not be used.

The following by-laws of proper radio design might be stated (transistors the emphasized component).

1) All radios of a given type should be as similar as possible within the limits of acceptable

performance criteria.

2) All transistors, which, with their respective parameter distributions, might be received and accepted by test to the purchase specification should provide acceptable performance of the radio in fulfillment of 1).
3) All transistors should be operated within their recommended ratings.
4) Rigid test procedures must exist to screen and prevent the use of latent defective transistors.

t seems proper to state that if the by-laws are heeded, designed circuit will have the desirable attributes of) minimum circuit performance variation as a function of all possible combinations of transistor parameters, and 2) minimized effects of transistor change with time. Thus we will have quality and a reliable product.

EXAMPLES OF PROPER CIRCUIT DESIGN

A number of specific radio circuits will be discussed. Our purpose is to show how parameter distributions are handled, performance variation minimized, and transistor limitations acknowledged.

F Amplifier

Although the literature covers this matter quite horoughly, a few of the salient design matters will be mentioned.

Our goal is a circuit with the best combination of selectivity, power gain, uniformity in performance, and cost. The transistor under consideration has ratings in excess of the circuit demands and has as significant parameter spreads, dc current gain 10-55 (manufacturer's test circuit) and IF power gain 4-27.5 db (manufacturer's test circuit). Knowing that power gain varies with current (see Fig. 1), we evaluate this variation and pick our design center operating point accordingly.

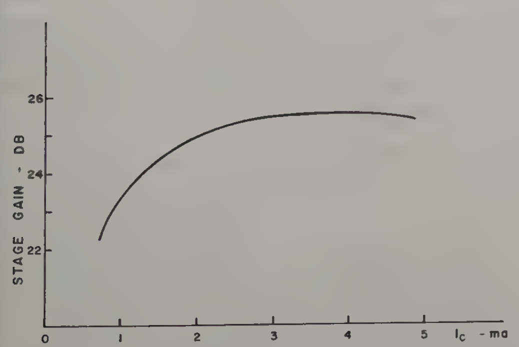


Fig. 1—IF amplifier gain variation vs collector current.

In order to minimize the gain variations, the operating point must be stabilized at the design center value. A choice prevails as to degree of stability and whether or not ac operation will be affected by the bias network. At this time, typical input and output impedance levels may be determined. Thus IF transformers giving maximum circuit gain and desired selectivity may be designed.

An acceptable IF amplifier stage is that of the second IF in GE P-776. Its circuit is shown in Fig. 2.

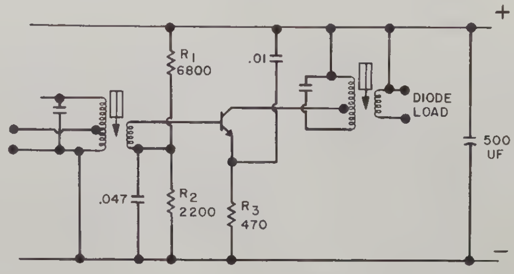


Fig. 2—Circuit diagram of P-776 second IF stage.

Units were selected to include the complete power gain spread, the complete h_{FE} spread, and low low and high high limits of same. The resultant data showed the current to vary between 1.5 and 1.8 ma, and the circuit gain between 21.1 and 26.9 db. The operating point is being maintained within 1.3 db of maximum gain point of the device. To show the significance of stabilization, R_3 was made 0 and R_2 was made infinity. Then R_1 was adjusted until a mean h_{FE} unit had the same current as it did in the original circuit. Then the data was retaken. The quiescent current was observed to vary between 0.8 and 3.1 ma and circuit gain from 18.1 to 25.1 db. The observed variations in operating point and circuit gain are plotten in Fig. 3 and 4 respectively.

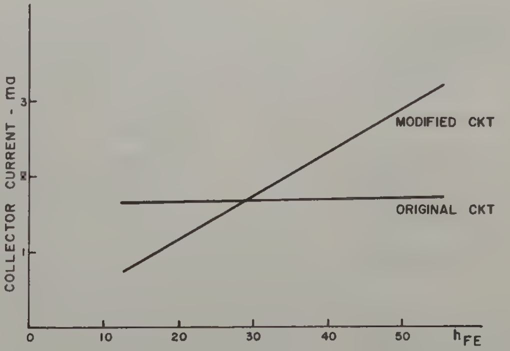


Fig. 3—Operating point variation vs dc current gain.

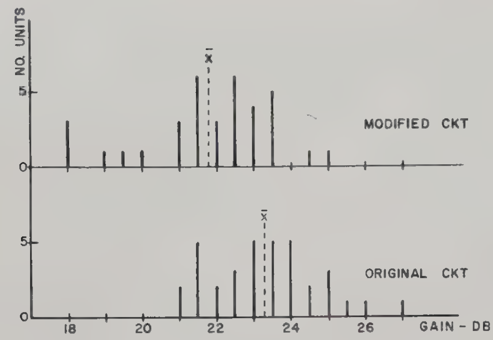


Fig. 4—Circuit gain distributions (nearest half db).

The wider gain spread and lower gains observed in the modified circuit are attributable to the wide current variations allowed. The original circuit with its excellent stability will minimize h_{FE} variation with time and thus allow the circuit to maintain its initial performance level. This is reliability.

Transformer Coupled Class A

In such a circuit, we are obliged to pay particular heed to voltage and power limitations as well as parameter control. Ideally, it is possible to swing twice the supply voltage. Practically, our circuit design must be such that twice the quiescent collector voltage is within the V_{CER} breakdown rating of the device. We must further assure that the dissipation at quiescent conditions (worst possible ambient) does not place the junction temperature beyond its rating.

The first phase of design is that of designing the output transformer knowing the desired power output and supply voltage values. The typical quiescent conditions which are thus determined, and the instantaneous voltage conditions which exist will permit selection of a suitable transistor type. The leakage and dc current gain controls on this selected type will then determine how well stabilized the operating point must be. It is mandatory to maintain uniform circuit performance, and to prevent thermal regeneration from placing the junction beyond its temperature rating. The resultant circuit will then

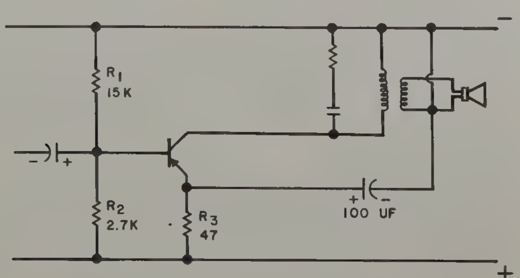


Fig. 5—Circuit diagram of P-805 output stage.

possess the high quality and reliability attributes we desire. The output stage of GE P-805 is a circuit demonstrating proper design fulfillment. It is shown in Fig. 5.

For 3 each of the low limit, mean, and high limit transistors (by h_{FE}) average data is summarized in Table 1.

TABLE I

	Average 10 Per Cent Power Out	Average Quiescent Current
Low Limit	37 mw	14.3 ma
Mean	56 mw	18.4 ma
High Limit	60 mw	20.1 ma

Of special note is the manner in which the circuit exhibits ideal classical behavior. In the bottom trace of Fig. 6, a mean unit is shown to contribute both saturation and cut-off effect at 10 per cent distortion. The top trace, that of a high limit transistor (with its correspondingly high quiescent current) shows greater presence of the saturation

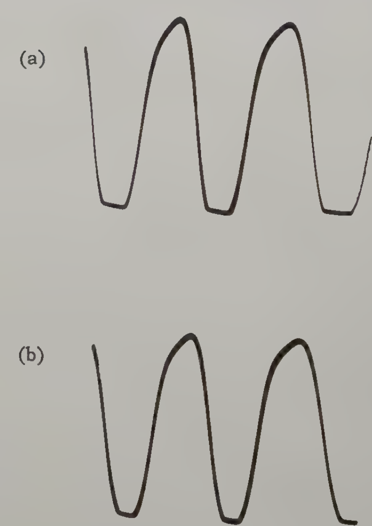
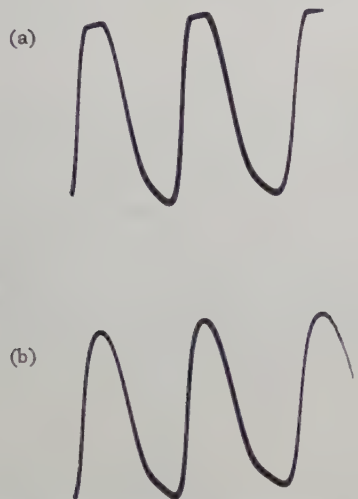


Fig. 6—Class A output waveforms. (a) 10 per cent power high h_{FE} unit. (b) 10 per cent power mean h_{FE} unit.

effect at 10 per cent power. In Fig. 7, the bottom trace is again that of the mean unit at 10 per cent power. The top trace is that of a low limit transistor. The predominance of the cut-off effect at 10 per cent power is clearly shown.

As part of the program of proper radio design, satisfactory performance must be maintained at 45° C or 113° F. This output transistor with 150 mw of dissipation at room temperature must remain within junction limitations at the elevated temperature. Tests on high h_{FE} and high I_{CO} (combined) units reveal that with the heat sink we have designed, the junction temperature is held to 65° C even though the transistor is at maximum

ower dissipation in the 45° C ambient. Admittedly is design is straightforward. Yet apparent sim-licity cannot preclude due consideration of 1) ansistor distributions 2) uniform circuit perfor-nance, and 3) transistor limitations. These are e measures which, when taken, assure a high uality design.



ig. 7 — Class B output waveforms. (a) 10 per cent power low h_{FE} unit. (b) 10 per cent power mean h_{FE} unit.

lass AB Push Pull

In addition to the proper consideration of tran-istor voltage and junction temperature limitations, e must also pay heed to the transistor's power ain variation with collector current. Classically, ain is shown as decreasing as current increases. practice a gain rise might be encountered just s frequently as a gain decay. For minimum dis-ortion effects, the power gains of the two tran-istors should be matched as closely as possible. particular, this matching of gain should occur t the current level where 10 per cent power ccurs for the circuit in question. Typically, audio ansistors of today have only over-all h_{FE} controls nd over-all input resistance controls. No precise ontrol of gain exists. This represents a challenge improve the possibilities of attaining high quality erformance. Fig. 8 shows a typical class AB circuit.

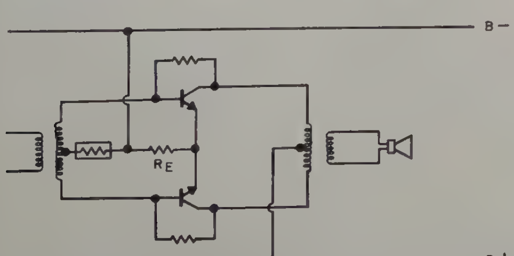


Fig. 8 — Circuit diagram of a class AB output stage.

The performance of various pairs of output transistors are shown in Figs. 9-11.

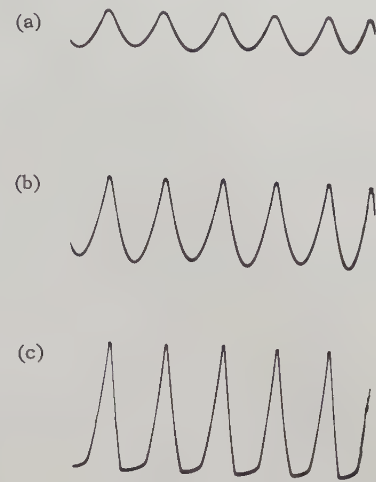


Fig. 9 — Waveforms across $R_E = 1\,\Omega$. Class AB push-pull. Matched gain transistors. (a) 50 MW. (b) 200 MW. (c) 515 MW. (10 per cent distortion).

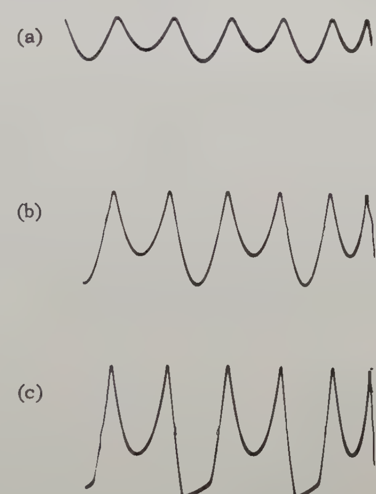


Fig. 10 — Waveforms across $R_E = 1\,\Omega$. Class AB push-pull. Transistors have equal h_{FE} at 35 ma. (a) 50 MW. (b) 200 MW. (c) 430 MW (10 per cent distortion).

Fig. 9 shows the waveforms across R_E equals 1 ohm for a pair of transistors with almost equal power gain. From top to bottom are the waveforms for 50-mw power output, 200-mw power out and 515-mw power output (10 per cent distortion). Notice expecial-ly that both transistors are contributing equally and clip evenly. Fig. 10 is for a pair of transistors with equal h_{FE} at $I_c = 35$ ma. As the top waveform (50mw) shows, the gain contributions are not the same. At 200 mw the gain difference is even greater. At the 10 per cent distortion point only 430 mw are deliv-ered with an extreme unbalance in gain. The com-parison of Figs. 9 and 10 shows irrevocably the need

for gain control on these devices. Fig. 11 shows the effects of increased negative feedback in reducing the gain mismatch effect on a third pair of transistors. The top waveform is for R_E equals 1 ohm and 5 per cent power output (400mw). The middle waveform is for R_E equals 10 ohms and 5 per cent power output (385 mw). The bottom waveform is for R_E equals 22 ohms and 5 per cent power output (295 mw). We note here the reduced mismatch, but also unfortunately loss of power output. The improvement though would be noticeable in improved distortions at lower power outputs. See Fig. 12.

(a)
(b)
(c)

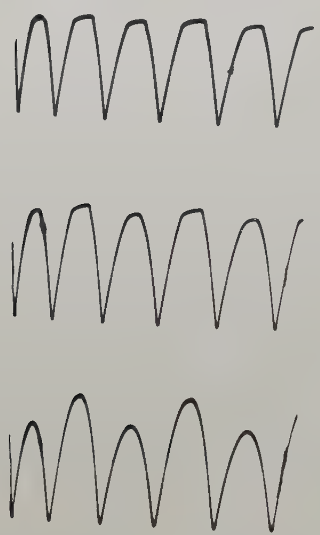


Fig. 11—Waveforms across R_E. Class AB push-pull. Transistors have unequal gain. (a) $R_E = 1\ \Omega$, 400 MW (5 per cent distortion). (b) $R_E = 10\ \Omega$, 385 MW (5 per cent distortion). (c) $R_E = 22\ \Omega$, 295 MW (5 per cent distortion).

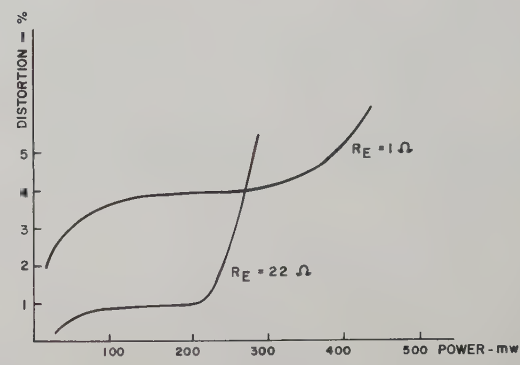


Fig. 12—Distortion vs power out.

The need for gain controls on the transistors for optimized class AB circuits is apparent. Until the transistor manufacturers comply with this need, negative feedback must be used to assure high quality circuitry.

CONCLUSIONS

In order to achieve high quality performance and reliability in transistorized home radios, the following matters must be considered intelligently.

1) Transistors should not be operated in excess of their limitations.
2) Distributions which exist on the various parameters should be known at the time of circuit design.
3) The circuit must be designed so as to minimize the performance variation observed with limit transistors.
4) Rigid inspection procedures must exist to prevent use of unacceptable transistors.
5) Aggressive integration must be made with transistor manufacturers. The purpose would be to encourage them to provide meaningful controls on transistors, and to strive otherwise for high quality.

Statistical Approach to Reliability Improvement of the Tantalum Capacitor

NICHOLAS P. DEMOS †

This paper is a progress report of the General Electric Capacitor Department's reliability improvement program for the tantalum foil capacitor. It is expected that a second progress report will be published in another year.

During the fall of 1958, the GE Capacitor Department undertook to develop their commercial tantalum foil capacitor into a high-reliability component which would meet the challenging reliability requirements of the missile and space projects being contemplated at that time.

As the first step, the Capacitor Department asked the Mathematical Analysis component of the General Engineering Laboratory to conduct a study appraising their operations and to submit recommendations for a Reliability Improvement Program.

The General Engineering Laboratory is an organization on the corporate level which is a source of technical assistance in engineering programs to the components of the General Electric Company. The Mathematical Analysis component provides this service in the areas of mathematics and statistics.

The study concerned itself with two factors:

1) the improvement and control of the rejections in the production line, and
2) the evaluation of the variables pertinent to reliability.

The importance of the first of these factors, improvement of in-process rejections, is widely accepted as a truism. Unfortunately, the magnitude of its importance isn't truly realized. The improvement of in-process rejections is of critical importance to the Reliability Improvement Program. Because of this belief, a good portion of this paper is devoted to extolling this postulate.

To illustrate the interrelationship between rejections and reliability, Mathematical Analysis hypothesized the following problem.

Consider the manufacture of two parts, a shaft and the bearing that is to hold it. There are three variables involved. The shaft's diameter and the bearing's inside diameter are the independent variables. The clearance between the shaft and bearing is the dependent variable. To simplify our illustration, let us make the following assumptions:

1) The clearance is a field variable and cannot be measured in the plant.
2) Engineering properly sets all the specifications.
3) The specifications are set so that the percentage of unsatisfactory clearances in the field will be 0.1 per cent.
4) The factory is experiencing a 5 per cent scrap rate on each, the shaft and the bearing.
5) All individual shafts and bearings shipped meet the specifications.

The planned distributions compared to the specifications are shown in the top portion of Fig. 1. The actual distributions resulting from a 5 per cent scrap rate are shown in the bottom portion of Fig. 1. The normal distribution and equal sigmas are assumed for all distributions.

It should be noticed that a 2.0 per cent failure rate would occur in the field. The confusing thing about these failures is that the parts would be found within specifications and an evaluation of the specifications would find them properly set.

Consider now a product with 10 such components related as a series. Using the product rule the designed reliability is $(0.999)^{10}$ or 99.0 per cent. With the 5 per cent scrap rate it becomes $(0.980)^{10}$ or 81.7 per cent. Again, all failures would be found to meet all specifications and all specifications would be evaluated as properly set.

In-process inspection and test characteristics serve as indicators of product quality and reliability. One of the most dramatic ways to improve product quality in a going operation is to reduce the rate of occurrence of in-process inspection and test rejections.

High reliability is the end result of proper engineering design, proper end usage, and proper manufacturing technique. A great deal of attention has been paid in the literature to the first and second factors as reliability

† General Engrg. Lab. General Electric Co. Schenectady, N.Y.

influences, with correspondingly less attention paid to the effect of manufacturing techniques on reliability. In the latter case, it is in fact often assumed that manufacturing quality defects can be routinely culled out in routine in-process or final inspection, with few such defects reaching the end user. This is definitely not true in most cases since manufacturing errors not only cause defects which may be immediately detected, but also others which weaken and degrade the product and only show up in product use by reducing the effective service life and over all reliability of the product.

Fig. 2, entitled "Principal Defects and their Causes," is a specific demonstration of this principal as it applies to the tantalum foil capacitor. (The chart was prepared by the Supervisor of Tantalytic Capacitor Engineering.) Across the top of the chart are found 45 processing errors inherently possible in the manufacturing process. Down the side of the chart are listed the defects that these 45 processing factors may cause in the product, these defects showing up either at in-process inspection, final inspection, or in end usage. It will be noted that 43 of the factors may cause defects found in-process, 40 factors cause defects found at final inspection, and 35 factors will also cause defects found only during actual product use; i.e., reliability type defects.

From a study of this chart, it was apparent that merely culling out defects at in-process and final inspection would not influence the effect of the underlying process factors in decreasing reliability. However, a program aimed at reducing in-process and final inspection defects by <u>eradicating their underlying causes</u> would also be reflected in improved field performance; that is, in higher reliability.

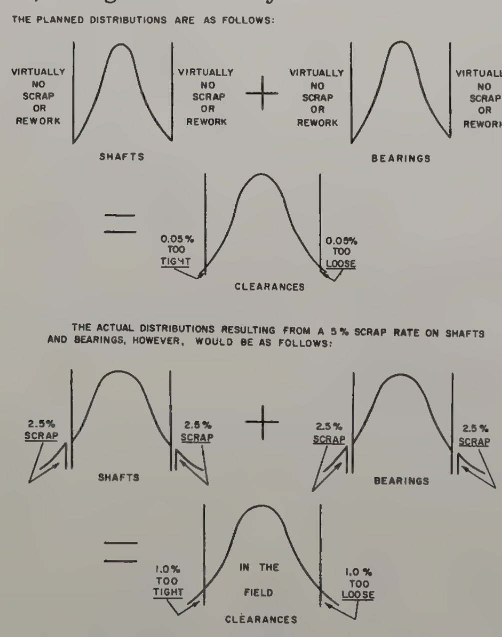


Fig. 1.

Figs. 3 to 5 are offered here as a case in point. They are taken from an article by Grunewald.[1] Fig. 3 shows an 88 per cent reduction in the rate of in-process rejections: from 3.2 per cent to 0.4 per cent.

Fig. 4, the customer's quality index (where higher figures represent poorer quality) shows a corresponding reduction of 92 per cent from a rating of 26 to a rating of 2. Fig. 5 shows a corresponding decrease in manufacturing losses.

Whether or not an improvement of this type can be effected can be determined by a statistical analysis of the in-process rejection characteristics. If the statistical analysis discloses a high degree of statistical instability, a dramatic improvement can be effected by the implementation of an effective statistical data system. Should the analysis disclose, instead, a high degree of statistical stability, little improvement could be achieved by this approach alone.

Figs. 6 to 8 are presented to illustrate this principle. Fig. 6 is a statistical $\overline{p}$ chart graphing a foreman's daily percentage of scrap. The first portion shows the daily scrap percentages for the month before the program was initiated; the latter portion shows the performance five months later. It should be observed that the process was pronouncedly unstable during the first portion and relatively stable during the latter portion. It should also be noticed that a 72 per cent reduction in the rejection rate was effected.

A master control system analysis is an efficient method for appraising the statistical stability of a process. It is described in a previous paper.[2]

The data comprising Fig. 6 is presented in Master Control System format in Figs. 7 and 8. Fig. 7 presents the data for the first part, the month prior to installation; Fig. 8 presents the latter part, the fifth month after installation.

In reference to Fig. 7, every entry that exceeded the appropriate statistical limits was circled. Those out on the high side were circled in red; those out on the low side were circled in green. A statistically stable process in this case should have produced only two circles; instead 118 occurred. It was on the basis of this analysis that the implementation of an effective process data system was recommended.

[1] R.L. Grunewald, "Improved Quality Control thru Performance Measurements and Effective Corrective Action," presented at the Amer. Soc. for Quality Control Natl. Convention, Montreal, Canada, June, 1956.

[2] N.P. Demos, "The Master Control System" presented at the New England Conf. of the Amer. Soc. for Quality Control, Albany, N.Y., October 23, 1954; also "The Master Control System in General Electric," <u>Industrial Quality Control</u>, Vol. 00, PP. 000–000, October, 1955.

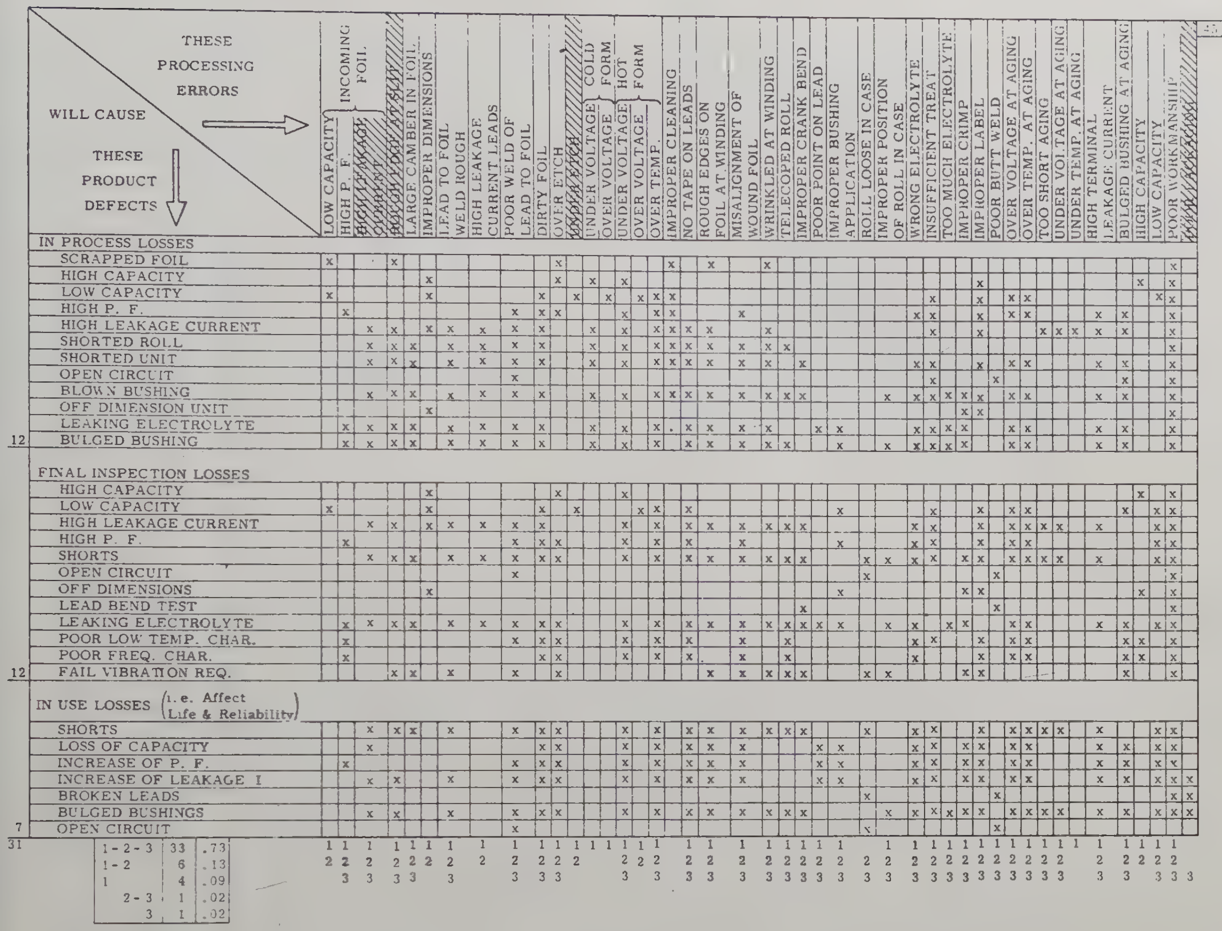


Fig. 2—Principal defects and their causes.

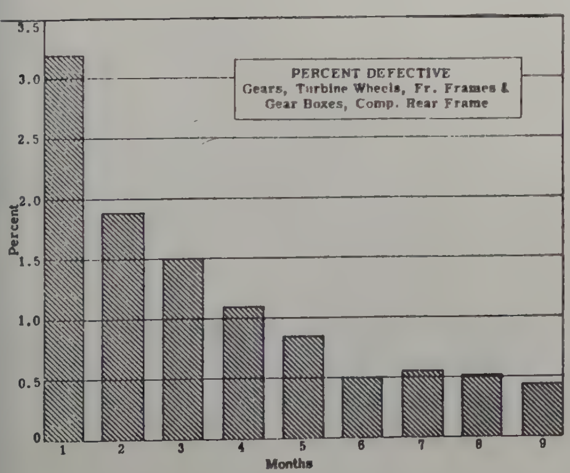


Fig. 3.

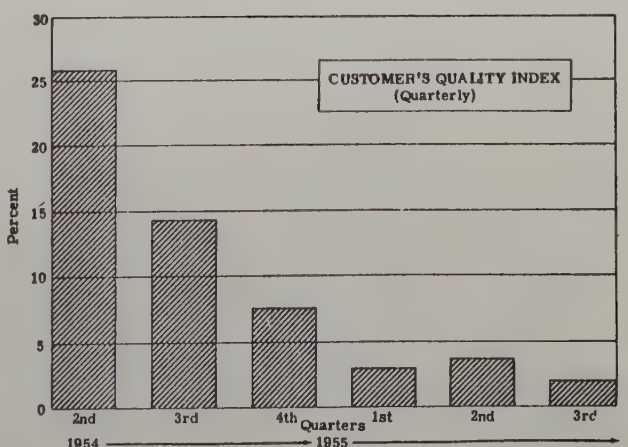


Fig. 4.

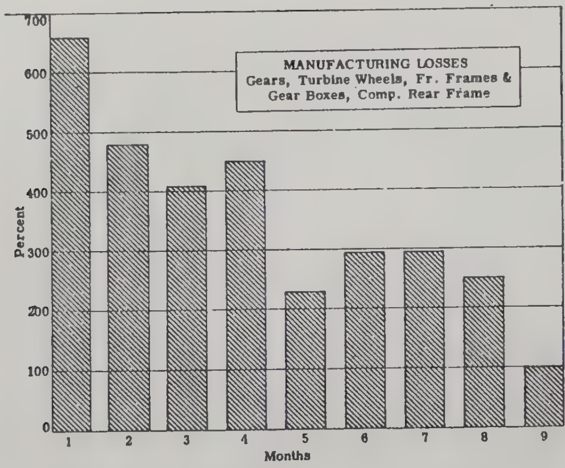


Fig. 5.

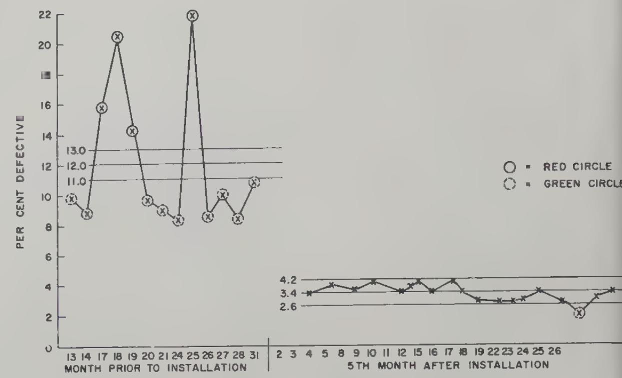


Fig. 6—Daily scrap.

$\overline{P}$	STATION	1	2	3	4	7	8	9	10	11	14	15	16	17	18	21	22	23	24	Total	$\overline{P}$	STD $\overline{P}$
1.0	CORE ASSEM.	25	50	40	23	27	35	40	23	32	40	30	21	6	28	36	130	16	20	622	0.56	0.6
0.7	SPACERS	35	30	150	42	62	56	51	58	20	54	124	25	28	27	125	224	23	48	1182	1.06	1.0
1.2	HOT STAKE	26	15	20	26	19	20	34	45	14	23	21	15	35	33	30	15	11	16	418	0.38	0.4
2.6	CRIMPERS	194	166	440	89	111	170	180	220	154	243	198	67	51	59	244	162	57	81	2886	2.59	2.6
0.1	SOLDER	3	3	25	8	4	9	7	3	0	18	15	1	7	2	4	15	4	15	143	0.13	0.1
0.4	TERM BEND WAXER	24	29	27	20	29	31	32	27	20	56	52	19	26	39	180	102	61	45	819	0.74	0.7
0.7	CANNER	42	45	70	37	31	30	27	38	21	[illegible]	32	15	25	37	54	49	9	9	613	0.55	0.6
3.6	TERM. BASE ASSEM.	327	100	240	207	64	84	324	136	90	190	390	307	110	82	68	63	62	58	2902	2.61	2.6
1.8	MICA BASE ASSEM.	163	50	120	103	31	41	161	67	45	95	195	153	55	41	33	31	30	28	1442	1.29	1.2
12.0	TOTAL	839	488	1132	555	378	476	856	617	896	761	1057	623	343	348	774	791	273	320	11027	9.91	10.0
PRODUCTION		7742	7361	3213	6246	7382	7510	7380	6881	5220	6426	7447	4055	6258	5160	4328	5332	6721	6623	111,283		

○ = RED CIRCLE
◌ = GREEN CIRCLE

Fig. 7

$\overline{P}$	STATION	2	3	4	5	8	9	10	11	12	15	16	17	18	19	22	23	24	25	26	Total	$\overline{P}$	STD $\overline{P}$
0.4	CORE ASSEMBLY	15	23	32	32	21	26	12	15	6	8	2	4	5	6	12	4	4	12	9	248	0.33	0.3
0.2	SPACERS	11	12	19	19	21	12	18	9	12	6	13	6	3	12	13	13	7	9	7	222	0.29	0.3
0.4	HOT STAKE	13	13	15	14	14	9	30	12	14	14	13	10	10	13	10	22	11	21	12	270	0.36	0.4
0.7	CRIMPERS	27	24	28	31	35	37	38	47	36	24	25	21	22	21	20	34	24	29	18	541	0.72	0.7
0.05	SOLDER	1			1			1	1	1											5	0.01	0.05
0.1	TERM. BEND WAXER	1	3	3	3	1	3	1	1	2	4	2	2		2	3	2	2	1	1	37	0.05	0.05
0.05	CANNER	1	1		5		3			4	3	3	2			1	3	3			29	0.04	0.05
1.2	TERM. BASE ASSEM.	60	50	25	30	22	30	40	38	40	48	37	25	35	30	50	20	10	15	12	617	0.82	0.8
0.4	MICA BASE ASSEM.	26	26	18	26	20	34	26	27	40	40	32	50	31	26	42	27	27	25	35	578	0.77	0.8
3.4	TOTAL	155	152	140	161	134	154	166	150	155	147	127	120	106	110	151	125	88	112	94	2547	3.38	3.4
PRODUCTION		4122	3815	3815	3993	3953	3975	4075	4165	3791	4006	3927	3976	3911	3943	4065	4123	4006	4167	3464	75,292		

○ = RED CIRCLE
◌ = GREEN CIRCLE

Fig. 8.

During the summer of 1959, a master control sys-
em was designed and installed in the commercial tan-
alum foil production line.

By January, 1960 a 60 per cent reduction of the
ine operation rejections had been accomplished. This
raph and that for the line operation inspection and
est stations are shown in Fig. 9. The names of the
tations have been withheld, their order has been
hanged, and the scales have been altered for propri-
tary reasons.

Fig. 8 shows that there has been substantial reduc-
ion of rejections at 6 stations and little or no reduc-
ion at 2 stations. The graphs for two of the stations
eflect epidemics.

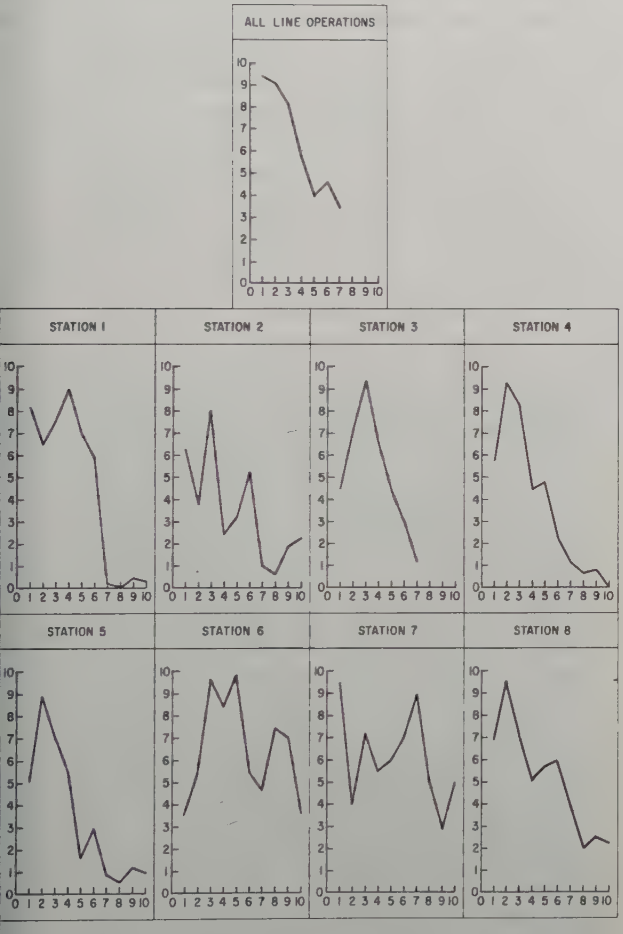


Fig. 9—In-process rejections.

Thus far, this paper has been concerned with the
nprovement of in-process rejections. The second
ictor of the study performed by Mathematical Analy-
s concerned itself with the evaluation of the variables
ertinent to reliability.

It was recognized that a reliability program could
ot be executed without an adequate life testing pro-
ram. The life testing program should provide suf-
cient information for an adequate period of time. It
should realistically test the product for the environment the product is expected to see.

In order to have an effective Reliability Control System, it would be mandatory to develop an adequate accelerated life test. In-process data would have to be rapidly evaluated so that the process might be controlled, hypotheses made and timely evaluated, and improvements made and evaluated. The program for developing a more efficient accelerated life test should be both a current and a long range program.

An analytical program should be conducted to determine the relationship between the normal life test and the accelerated life test. This information should be used to help determine the adjustments to be made on the current accelerated life test.

A monitoring system should be developed. It should provide the numerical indices from which reliability could be evaluated. All other data would be correlated against these indices to evaluate their effect upon the reliability. The indices should be adjusted to reflect the analytical results of the "normal life test—accelerated life test evaluation program." Provision should be made for replacing at any time the current accelerated life test with a faster or more valid test.

The data from the various sources should be integrated into one system. The method of integration should be such as to maximize the sensitivity of the related variables for evaluation. The data areas that should be integrated into this system are incoming inspection data, in-process data, testing data, and field or actual use data.

All the data should be evaluated one source against another; all data should also be evaluated against the life test data. These evaluations should be reduced to regular procedures. The complexity of this analysis would call for a program to develop the analytical methodology of this integrated data system. This program and the data processing procedures it would call for would require the services of an electronic computer.

Finally, to produce beneficial action the information emanating from this data system would have to be effectively presented to the respective appropriate personnel. The complexity of this task would call for a program to develop the presentation methodology of this integrated data system.

Both phases of the Tantalum Capacitor Reliability Improvement Program have progressed beyond the description released for this paper. It is expected that the next paper released will contain a description of advanced methods for reducing in-process rejections and also a description of the integrated data system for evaluating the variables pertinent to reliability.

The Motorola "Golden M" Tube Reliability Program

J. RICHARD BELLEVILLE†

Receiver tube failures have historically been the major cause of television receiver failures in the customer's home. The Motorola "Golden M" tube evaluation program was formulated to reduce the field and factory failure rate of receiving tubes and thus improve the reliability of the television receiver. This program evolved from experimental work done by the Motorola Television Development Engineering Department and from an analysis, in cooperation with the tube vendors, of over 70,000 field failure tubes. The receiver tube failure rate in the field has been reduced by a factor of two to one since the inception of this program, in spite of the fact that the warranty period was extended from three months to twelve months.

This paper will deal primarily with the enforcement of the Golden M program as an acceptance criteria in Incoming Inspection.

The basic document is the specification written by the Motorola Television Engineering Department. A specification is written for each tube type. Tubes are purchased to this specification which is referenced on the purchase order. Each specification covers the following areas:

1) characteristics tests by the curve trace method,
2) "blast" testing under high dissipation conditions,
3) 48-hour accelerated life tests.

The second basic document is the Acceptable Quality Level (AQL) which is written by the Tube Application Department and which details acceptance numbers and sampling plans for each specification. These Acceptable Quality Levels together with the specifications are issued to the vendor by the Motorola Purchasing Department.

Each of the three general areas of the specification as mentioned above has its own particular problems of enforcement; therefore, each will be considered separately.

CHARACTERISTICS TESTS

Characteristics tests by the curve trace method have been described in the literature[1]. In the Incoming Inspection Department it was decided to test a full statistical sample according to Military Standard 105A Inspection Level II. Over thirty different tube types were to be tested. Therefore, methods for combining tests and minimizing set-up and testing time had to be devised. The basic test circuit is shown in Fig. 1 and the actual test equipment is shown in Fig. 2.

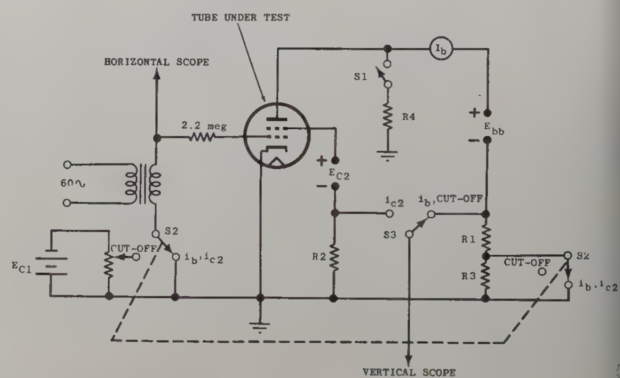


Fig. 1—Motorola "curve test" tube tester circuit.

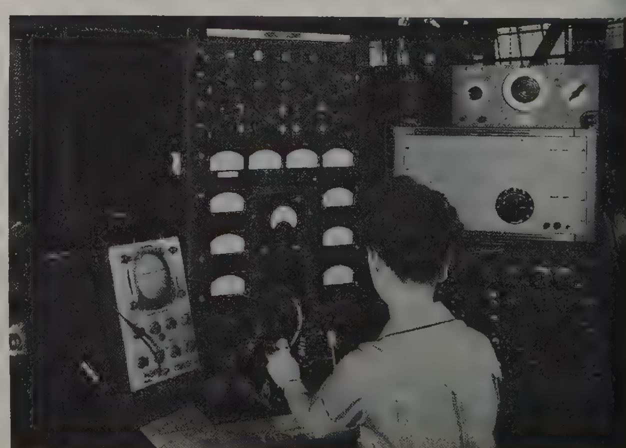


Fig. 2—Motorola universal test tester.

† Motorola, Inc., Franklin Park, Ill.

1 R. O'Fallon, "Receiving Tube Specifications," "Proc. Natl. Electronics Conf. location? Vol. 12, PP. 00—00; date 1956

Basically, the curve trace method of testing con-
sts of displaying grid one to other element transfer urves on a dc oscilloscope. This requires current ampling resistors in series with the proper elements nd an accurate method of calibrating the oscilloscope. series of precision resistors was chosen so that r each current value to be measure, the resultant oltage developed was large enough to drive the scilloscope and yet not so high as to change appre- ably the dc voltage at the element of the tube. For gh current tubes, resistor values were as low as 7 ohms. With this low value, the contact resistance the test jig might be appreciable as compared to e sampling resistor. Therefore, calibration of the scilloscope by voltage, based solely on ohms law lculations, might produce appreciable errors. To vercome this problem, a circuit was devised to ass a known, metered current through the sampling esistor in the jig and to allow the oscilloscope to be alibrated directly in terms of circuit current. In ig. 1, calibration is accomplished, without a tube the circuit, by depressing switch S1 which places esistor R_4 in series with the I_b meter, sampling esistor R_1 and plate supply E_{bb}. Current in the rcuit is set to a specified value on meter I_b by

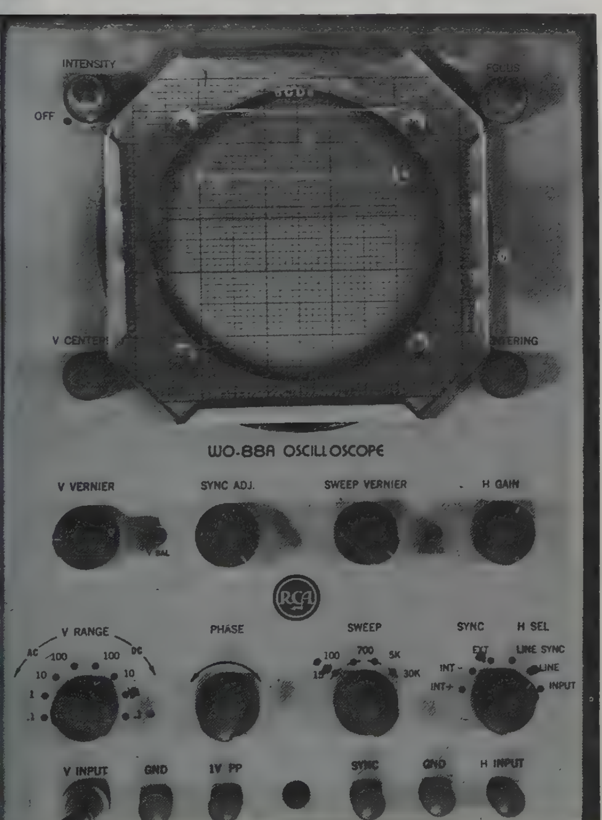


Fig. 3—Oscilloscope with removable mask.

varying the plate supply voltage E_{bb}. Because a large number of tube types, with widely varying values of current, had to be tested, it was found convenient to make removable oscilloscope masks for each tube type Fig. 3. This allowed calibration of the vertical sweep of the oscilloscope at conveniently read points on the current meter and at the same time permitted the specification limits to be shown on the mask for convenience in attributes testing.

The engineering specification also requires a plate current to screen current minimum ratio under the specified test conditions. Assuming this ratio to be A, the ratio of the sampling resistors in the plate (R_1) and screen (R_2) are selected so that R_2/R_1 is equal to A. By momentarily switching the oscilloscope vertical input leads from the plate to screen circuit, the relative amplitude of the currents can be noted. If the plate current pattern is greater in amplitude than the screen current pattern, the tube is acceptable. For cut-off testing, the vertical calibration of the oscilloscope may be increased in sensitivity by inserting resistor R_3 in series with sampling resistor R_1 by means of switch S_2. The ratio of R_3 to R_1 is selected such that the cut-off current specified will fall at some conveniently read point on the oscilloscope. This level of current is marked with a horizontal line on the mask. The horizontal amplifier of the oscilloscope can be adjusted so that the horizontal trace is calibrated in terms of grid voltage applied to the tube under test. Bias supply E_{c1} is adjusted so that with S_2 in the cutoff position, the cut-off limits will both fall on the face of the oscilloscope. These limits are then marked with vertical lines on the mask. To check cutoff, the operator needs only to know that the transfer curve should cross the horizontal (current) line between the two vertical (voltage) lines to be acceptable.

Testing for characteristics in incoming inspection is done on an attributes basis. Characteristics are classified as either major (2.5 per cent AQL) or minor (6.5 per cent AQL) based on circuit requirements and past experience. Characteristics which are essential for operation are considered to be major items. Characteristics which have a high probably of acceptable operation, depending upon overlapping tolerances, are considered to be minor items. At the completion of the characteristics tests, all major rejects are totaled and all minor rejects are totaled. If neither exceed the acceptance numbers given in Military Standard 105A, the lot is considered acceptable for characteristics.

BLAST TESTS

"Blast" testing consists of "curve trace" testing under high dissipation conditions — 1.5 to 2 times

rated screen and plate dissipation simultaneously. "Blast" testing is designed to detect improperly processed tubes which would develop gas or grid emission that would shorten life in the television receiver. The test lasts for two minutes per section (four minutes total for a dual section tube) while the operator observes the oscilloscope pattern for indications of gas or grid emission. The test is timed by stop watch. A tube which completely loses grid control before the end of two minutes is removed immediately from test. Because of the time duration of the test, it is made only on a fixed sample of twenty tubes from each lot. The lot is accepted for "blast" if not more than two of the twenty tubes failed. In general, lots of tubes will either pass this test with less than two rejects or fail with a large number of rejects. Therefore, the exact acceptance number is not critical as long as it allows for the occasional reject.

ACCELERATED LIFE TESTS

As a result of a study of the analysis of field failure receiving tubes, the Motorola Television Development Engineering Department discovered that the majority of the causes for failure could be grouped into relatively few categories. It was found necessary to devise both a "cycled" and an "uncycled" test to cover all categories. Forty-eight hours was arbitrarily selected as a practical limit for test duration, and the tests were designed around this period.

The uncycled life test is designed to detect sublimation, interface and improper processing of cathodes. Under this test, a tube is operated at 125 per cent of rated heater voltage for 48 hours. All elements except the heater are tied to the cathode, and a 450-volt dc supply with specified internal impedance is connected between heater and cathode with the cathode positive. Tubes are evaluated according to the amount of plate current shift and contact potential shift during test and whether or not heater-cathode failure occurred. This method of evaluation requires the recording of data for each tube before and after test. Therefore, it is made on a fixed sample of 20 tubes and accepted if not more than two tubes fail. Since limits of plate current shift are specified in terms of per cent, it has been found convenient to record the plate current in terms of divisions on the oscilloscope mask. A conversion factor is included on the data sheet which permits conversion from divisions to current, if desired.

The cycled life test is designed to detect potential, early-life failures due to poor welding, walking cathodes, near mechanical shorts and other workmanship defects. The 48 hour cycled test cycles the tube one minute on and four minutes off at 175 per cent of rated heater voltage. All elements except the heater are tied to the cathode and line voltage is connected between heater and cathode through individual fuse and neon indicator circuits for each tube. A view of two bays of cycled aging racks is shown in Fig. 4.

Tubes are evaluated as operable or inoperable at the completion of the cycled test. Experience has shown that sublimation can sometimes cause a tube to appear to be mechanically inoperative. Therefore, all inoperative tubes are sparked with a spark coil and retested. If the tube tests as an operable tube after sparking, it is assumed that sublimation was present, but this is not counted as a reject on the cycled test. The cycled test is the only test specified which

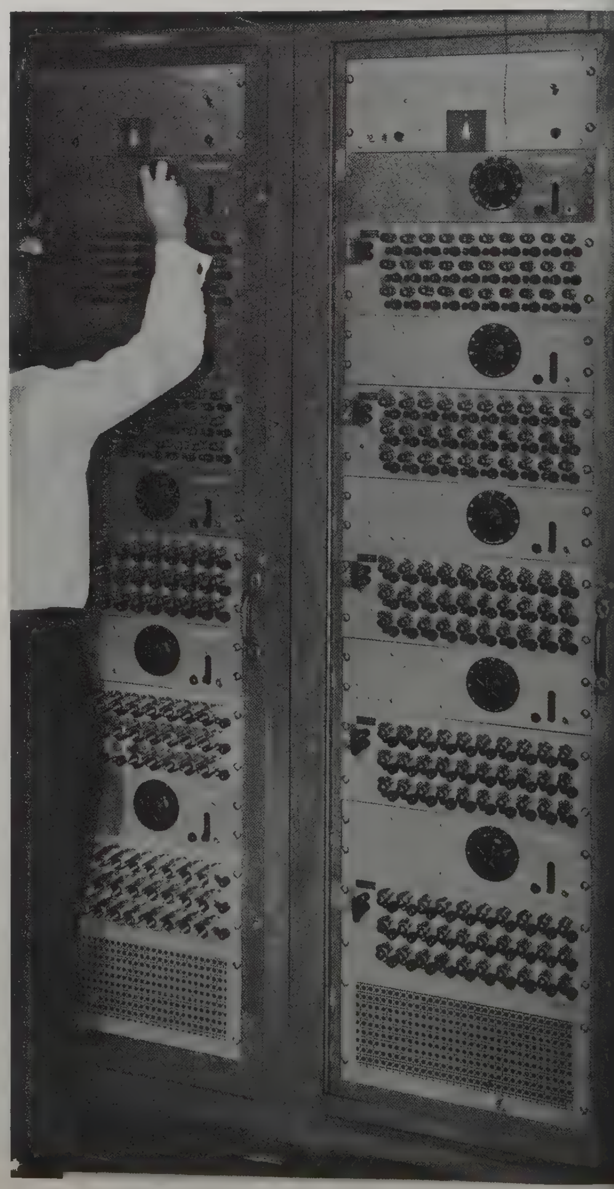


Fig. 4—Accelerated life test cycled racks.

considered destructive. A fixed sample of twenty bes from each lot is placed on the cycled test. The t is considered acceptable if not more than two tubes e found to be inoperative at the completion of the test.

VISUAL ANALYSIS

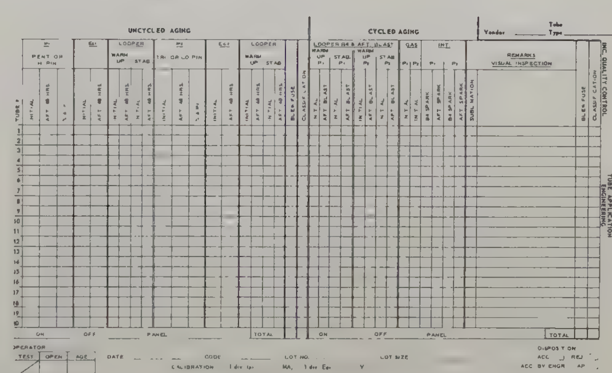
An important follow-up on the cycled life test tubes the visual analysis. The tubes are cut open with a t wire and examined under a magnifying glass Fig. 5. ates and other elements are cut away until the ca- ode and grids can be examined. The objective of this sual analysis is to find mechanical or workmanship fects. Over a period of time, a list of common defects d a criteria for judgment was developed and given to e vendors. Defects were termed either "rejectable" "information only." "Rejectable" items are those ich are likely to cause catastrophic failures in the eld and include near shorts, defective welds, loose rts, etc. "Information only" items are those which present generally poor workmanship or loss of safe- factor but which are not likely to cause catastrophic ilures. This latter classification would include slight- thumbed grids and poorly located plate tabs. Accept- ce criteria for various tube types has been established r the visual inspection. The results of the visual in- ection is fed back to the vendor so that corrective tion can be taken.

CONCLUSION

The "Golden M" program is a unique program tween a television receiver manufacturer and the be vendors. In a comprehensive program of this ture, it is essential that the acceptance criteria ed by Motorola be made known in detail to the ven- r. A number of papers covering various phases of e program were written and issued to the vendors. many instances, the exact test procedure and me- od of interpretation of the results is important. Specialized forms have been helpful in recording data in the Motorola Incoming Inspection Department. A form for recording life test, blast test and visual analysis results is shown in Fig. 6.

We appreciate the cooperation of the tube vendors in working with us on the "Golden M" program and in achieving a higher level of television receiver reliability.

Fig. 5 — Visual inspection.



UNCYCLED AGING | CYCLED AGING | Vendor | Tube Type

REMARKS — VISUAL INSPECTION

MOTOROLA INC. QUALITY CONTROL

ACCELERATED LIFE TEST — TUBE APPLICATION ENGINEERING

Fig. 6 — Accelerated life test data sheet.

Availability — A System Function

ROBERT P. BIELKA, † *Senior Member IRE*

INTRODUCTION

During the past several years, there has been increasing emphasis placed upon reliability. Reliability requirements have been advancing with such rapidity that many state-of-the-art components are unable to achieve the required life without resorting to redundancy or other similar techniques resulting in a net increase of the total number of components in the equipment.

To a somewhat lesser degree, maintainability has been a system requirement. To date, however, no satisfactory method has been found for establishing a numerical figure for this requirement. As a portion of this paper, it is proposed to do so.

A third area, one in which limited activity has been found, is that of availability. In essence, this may be considered the probability of having an equipment ready for operation when needed. This information would be a valuable aid in scheduling aircraft, ordering spare equipment, or deciding between systems.

It is the purpose of this paper to outline a method for evaluating a system or equipment for its availability. In addition, several side issues on reliability and maintainability, as affected by complexity, will be covered.

OPERATIONAL RELIABILITY

Reliability is generally defined as the "probability of a device performing its purposes adequately for the time required under the environment specified." It should be noted that "specified" appears in the description of environment. It is necessary that the environment and operating conditions be established prior to design in order that all factors may be considered. "Encountered" does not define the environment and operating conditions sufficiently for sound engineering.

The formula [1] most widely accepted for reliability is $R_p = e^{\lambda_p t_1}$

Where R_p is Operational Reliability,
e is the base of natural logarithms,
λ_p is the operational failure rate, and
t_1 is the operating time.

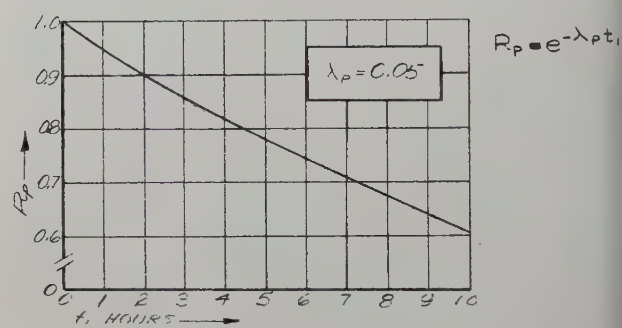
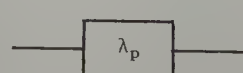


Fig. 1.

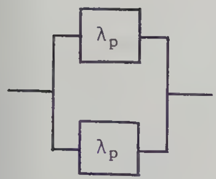
When this formula is plotted, the curve takes the familiar shape shown in fig. 1. Redundancy, or the incorporation of alternate means to accomplish the desired effect, results in a formula of increased complexity for calculating operational reliability. For purposes of illustration, three relatively simple cases will be covered, 1) no redundancy, 2) dual redundancy using two continually operating identical units in parallel, one of which will suffice, and 3) triple redundancy with three continually operating identical units in parallel, one of which will suffice.

1) 

$R_p = e^{\lambda_p t_1}$

† Boeing Airplane Co., Renton, Wash.

1 In order to differentiate operational from maintenance reliability, it is necessary to add subscripts.



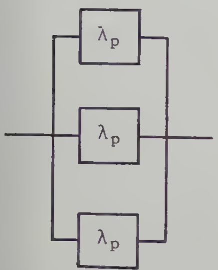
$R_p\ \text{total} = 1 - Q_p^2 = 1-(1-R_p)^2$ or

$R_p\ \text{total} = 2R_p - R_p^2$

where

R_p = single unit operational reliability

and Q_p = single unit operational unreliability or $(1-R_p)$



$R_p\ \text{total} = 1-Q_p^3 = 1-(1-R_p)^3$ or

$R_p\ \text{total} = 3R_p - 3R_p^2 + R_p^3$

where R_p and Q_p have the same definitions as in 2).

Upon examination it can be seen that, for simple arallel operating redundancy, R_p total = $1-Q_p^n$ where is the number of units in parallel and Q_p is oper-ional unreliability. This method allows great dvances in over-all operational reliability with nits of relatively low individual reliability. As an xample, consider the following:

no redundancy

$\lambda_p = 0.05$

t_1 = 10 hours;

$R_p = e^{-\lambda p t_1} = e^{-0.5}$

$R_p = 0.606$

and $Q_p = 0.394$;

) dual redundancy using two continually operating identical units, one of which will suffice:

$R_p\ \text{total} = 2R_p - R_p^2 = 1.212 - 0.367 =$ 0.845 to 3 places;

) triple redundancy using three continually operating identical units, one of which will suffice:

$R_p\ \text{total} = 3R_p - 3R_p^2 + R_p^3 = 1.818 - 1.102 + 0.223 =$ 0.939 to 3 places.

Comparing the three cases above, it can be seen at redundancy increases the ten-hour operational eliability from 0.606 for the single system to 0.845 r the dual and to 0.939 for the triple redundant ystem. This is a large increase in over-all oper-tional reliability but it not obtained without cost, as ill be show in the following section.

MAINTENANCE RELIABILITY

Maintenance reliability is the "probability that aintenance will not be required following a specified eriod of time when operated under the specified vironment." Maintenance reliability cannot be nored in view of the need for redundancy to achieve e required operational reliability with present components. Since the equipment must be returned to its original condition after use and since one or more of the redundant components may have failed, maintenance reliability considers all components, redundant or not, as a simple series string. Many types of equipment require maintenance for correction of conditions which in themselves do not affect normal operation but are not acceptable as an initial condition upon commencement of operation. These would be such items as small hydraulic leaks, adjustments near limits, etc. Since maintenance would be required to correct these items as well as those which affect operations, the maintenance failure rate, λ_m, is, at best, equal to operational failure rate, λ_p, and in most instances greater. The method for calculating maintenance reliability is the same as for simple series operational reliability as follows: $R_m = e^{-\lambda m t_1}$

Where R_m = maintenance reliability,

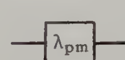
e = base of natural logarithms,

λm = maintenance failure rate,

t_1 = operating period.

For the three cases of simple, dual, and triple redundancy previously discussed, assuming the maintenance failure rate equal to the operational failure rate, the following maintenance reliability analysis are made.

1) Reliability Diagrams



Operational and Maintenance

therefore

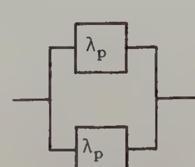
$R_{p_1} = e^{-\lambda p t_1}$ for $\lambda_p = 0.05$ and t_1 = 10 hours

$R_m = e^{-\lambda m t_1}$ $R_{p_1} = 0.606$

$\lambda_m = \lambda_p$ $R_m = 0.606$

$R_m = R_{p_1}$ $Q_m = 0.394$

2)



Operational

$R_p\ \text{total} = 2R_{p_1} - R_{p_1}^2$ R_p total = 0.845

Maintenance

since

$R_m = (e^{-\lambda m t_1})^2$

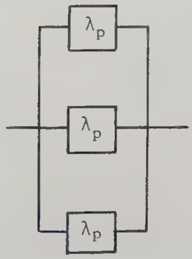
$\lambda_m = \lambda_p$

$R_m = R_{p_1}^2$

$R_m = 0.367$

$Q_m = 0.633$

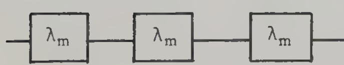
3)



$$R_p \text{ total} = 3R_{p_1} - 3R_{p_1}^2 + R_{p_1}^3$$

$$\underline{R_p \text{ total} = 0.939}$$

Operational



since

$$R_m = (e^{-\lambda_m t_1})^3$$
$$\lambda_m = \lambda_p$$
$$R_m = R_{p_1}^3$$

Maintenance

$$\underline{R_m = 0.223}$$
$$Q_m = 0.777$$

Thus, it is evident that while the single system with no redundancy has a low operational reliability, 60.6 per cent, it has the highest maintenance reliability, also 60.6 per cent. Conversely, the triple redundant system has the highest operational reliability, 93.9 per cent, and the lowest maintenance reliability, 22.3 per cent. If it is assumed that a single repair requires the same average repair time in either case, the triple redundant system will require maintenance about twice as often and about three times the quantity as the simple, no-redundancy system. The solution would be either to increase the operational reliability of the simple system or decrease the maintenance time requirement of the triple redundant system. Since the operation reliability of the simple system is assumed to be based on presently available components, raising this figure would be expensive in both developmental time and money. The other alternative is to design the triple redundant system for ease of maintenance, or to increase its maintainability.

MAINTAINABILITY

Maintainability, a subject of much discussion, can be defined as "the probability of specified performance being restored by a specified time, assuming a failure has occured." Since elapsed time is affected by the number of persons assigned to the job, and since much equipment cannot be maintained by more than one person at a time, it is felt that elapsed time is more indicative of the problem. Maintenance can be completed in a wide range of elapsed time from less than five minutes, in the case of simple adjustments at the installation, to hundreds of hours, in the case of complete rebuild at a distant repair facility. Complete destruction of the equipment would be the upper limit of repair time—infinite. The average time to repair can be determined from time studies on a statistical basis. Among other details, maintainability is affected by accessibility, since lower accessibility requires more time to remove the offending component for repair, the ease of localizing the difficulty, both to the major unit and to the failed component within the unit, the proficiency of the maintenance personnel, and adequacy of spares supply both in completeness and ease of acquisition.

Since the prediction of actual elapsed time to effect repairs is not possible, the problem becomes one of probability and can be handled by statistical methods. Assuming the repair rate is constant, the probability of completion of maintenance increases with elapsed time and is representable by the formula $M = 1 - e^{-\mu t_2}$

Where M = maintainability,
μ = maintenance rate, repairs per hour = 1/mean time to repair, and
t_2 = specified maintenance elapsed time or hours available for maintenance.

The curve for this formula takes the shape shown in Fig. 2.

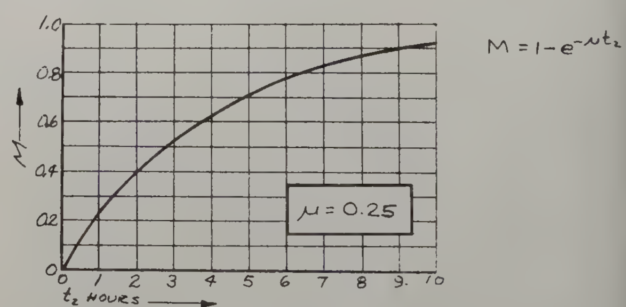


Fig. 2.

AVAILABILITY

Availability is the "probability of the equipment being ready for operation after a specified time, t_z, upon completion of previous usage of a specified time, t_1." It can be seen that this is affected by two probabilities

1) probability of not requiring maintenance, or maintenance reliability, and
2) probability of maintenance being completed, assuming it was necessary, or maintainability.

One method of explaining availability is as follows: ssuming a large number of units of one type, main- enance reliability can be considered the percentage of nits not requiring maintenance after operation of a pecified time.

Maintainability can be considered as the percentage f those units requiring maintenance having that mainten- nce completed by a specified time. Availability at a articular time is the sum of two: the percentage not equiring maintenance plus the percentage upon which aintenance has been completed. The following formula, en, is that describing availability.

$$A = M(1-R_m) + R_m \cdot$$

/here A = availability,

M = maintainability for time, t_z

$(1-R_m)$ = maintenance unreliability, or percentage of units requiring maintenance after operation of time, t_1, and

R_m = maintenance reliability for time, t_1.

xamination of the formula reveals that, as maintenance eliability increases, the probability of requiring main- nance decreases and availability is increased. Further, maintainability increases, availability increases.

As an example of the use of this theory, the following nditions are selected:

λ_m = 0.05 failures per hour (maintenance failure rate),

t_1 ≐ 10 hours (time of operation),

μ = 0.25 repairs per hour (maintenance rate),

total elapsed time = 5.5 hours,

fixed time (transportation, spare part issuance and recording time) = 1.5 hours,

t_2 = 4 hours (available elapsed time for servicing = total elapsed time minus fixed time),

$$R_m = e^{-\lambda_m t_1}$$

$$R_m = e^{-(0.05)(10)} = e^{-0.5}$$

$$R_m = 0.606$$

$$M = 1-e^{-\mu t_2}$$

$$M = 1-e^{-(0.25)(4)} = 1-0.367$$

$$M = 0.633$$

$$A = M(1-R_m) + R_m$$

$$A = 0.633(1-0.606) + 0.606$$

$$A = 0.633(0.394) + 0.606$$

$$A = 0.855$$

In other words, 85.5 per cent of the time, the unit ill be available for operation after 5.5 hours elapsed me, including a fixed time of 1.5 hours, after ten ours usage.

To ascertain the effect on availability of changing aintenance reliability and maintainability, the hanges in Table I are made.

TABLE I

Single System	Dual Redundant	Triple Redundant
λ_m = 0.05	0.10	0.15
μ_1 ≐ 0.25	0.25	0.25
μ_2 = 0.50	0.50	0.50

For these conditions, the values for availability are

A	B	C
λ_m = 0.05	λ_m = 0.10	λ_m = 0.15
μ_1 = 0.25	μ_1 = 0.25	μ_1 = 0.25
t_1 = 10 hrs.	t_1 = 10 hrs.	t_1 = 10 hrs.
t_2 = 4 hrs.	t_2 = 4 hrs.	t_2 = 4 hrs.
A_A = 0.855	A_B = 0.768	A_C = 0.715

D	E	F
λ_m = 0.05	λ_m = 0.10	λ_m = 0.15
μ_2 = 0.50	μ_2 = 0.50	μ_2 = 0.50
t_1 = 10 hrs.	t_1 = 10 hrs.	t_1 = 10 hrs.
t_2 = 4 hrs.	t_2 = 4 hrs.	t_2 = 4 hrs.
A_D = 0.943	A_E = 0.908	A_F = 0.887

The plots of these conditions are shown in Fig. 3.

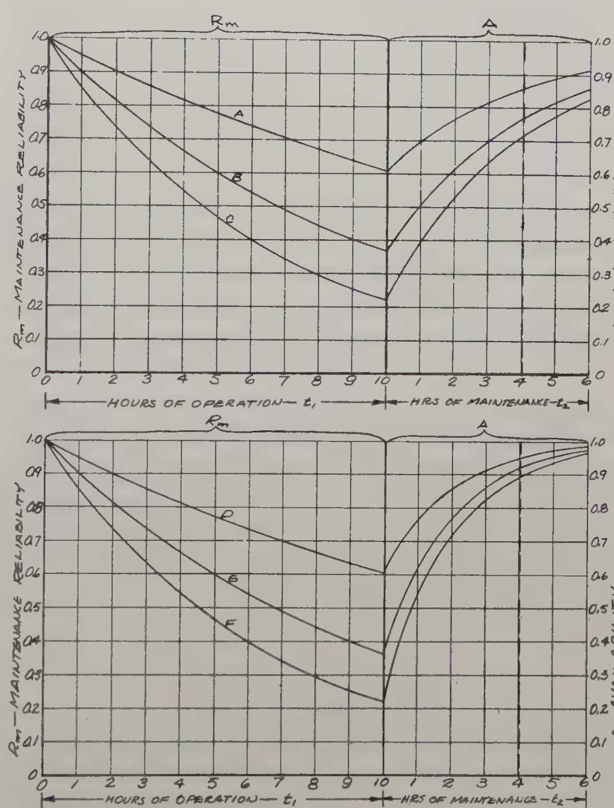


Fig. 3.

It can be seen that in case A, 90 per cent availability is not achieved until 5.5 hours of maintenance has been expended. By increasing the maintenance rate, μ, from 0.25 to 0.50, it is possible to obtain 90 per cent availability in case F, the worst maintenance reliability, after 4.15 hours of maintenace. By analysis of the remaining curves, the effects of both

maintenance reliability, R_m, and maintainability, M, can be seen.

This paper does not purport to outline all the methods for increasing maintainability; there are many. Some of the more obvious, in addition to accessibility of the equipment and ease of localization of the troubles, would be system breakdown philosophy, quality of maintenance personnel, availability of spares, and the working environment.

Availability is, therefore, a system function from the designer to the user. Each has his part in the problem and either can help-or hinder availability, depending upon his approach to the problem.

Survey of Reliability in the Engineering Curricula

CHARLES A. KROHN† MEMBER, IRE

INTRODUCTION

As the broad area referred to as reliability engineering develops, the question arises as to what is the role of the engineering college. The writer has previously ventured some opinions on this question[1] (see appendix I). This paper was also sent to electrical engineering department heads and engineering deans throughout the country in an attempt to introduce further the engineering colleges to the area and problems of engineering for high reliability.

Some engineering colleges presently have direct or related reliability subjects in the existing curriculum. A simple postal card questionnaire was sent to electrical engineering department heads and engineering deans with the previously mentioned paper. The objective of this survey was to establish the extent of reliability and statistics treatment in the engineering curriculums, particularly in electrical engineering. Such information will assist the various activities and individuals concerned with improving engineering education.

SURVEY RESULTS

The questionaires and cover letters sent to electrical engineering department heads and engineering deans are shown as Appendix II and Appendix III, respectively. Distribution was according to the Journal of Engineering Education, 1958 Yearbook and Membership Directory. Response from Electrical Engineering Department Heads was 49.3 per cent (74/150) and from Engineering Deans was 56.1 per cent (82/146). Most replies were dated April 1959.

Electrical Engineering Departments

Survey returns from electrical engineering departments are shown in Fig. 1. The per cent quantities shown are the percentage of the questionnaires returned that had the particular blank checked. Seventy-four questionnaires were returned. Note that it is possible for the percentages of the replies for a single question to add to more than 100 per cent, as more than one blank may have been checked. Also, the percentage of replies with respect to the graduate division may be somewhat misleading, in that some colleges replying do not have electrical engineering graduate work.

	None Marked
1. Is the subject of reliability treated in any E.E. course?	
Ungrad Yes: (optional course) 9.5% (required course 23% No: (no plans for future) 60.8% (planned, opt) 5.3% (planned, reqd) 2.7%	(0%)
Grad Yes: (optional course) 13.5% (required course) 2.7% No: (no plans for future) 59.4% (planned, opt) 8.1% (planned, reqd) 0%	(16.2%)
1a. If yes to 1, what type of course is it treated in and approx. how many class room hours are spent on it?	
Ungrad 0% Separate reliability course. Hours — 32.4% Rel. included in ckt, sys, etc. crs. Hrs. (on rel) avg 6.8	(67.6%)
Grad 1.4% Separate reliability course. Hours 45 14.9% Rel. included in ckt, sys, etc. crs. Hrs. (on rel) avg 7	(83.8%)
2. Is a statistics course available to E.E. students?	
Ungrad Yes: (optional course) 87.8% (required course) 5.4% No: (no plans for future) 6.8% (planned, opt) 0% (planned, reqd) 1.4%	(0%)
Grad Yes: (optional course) 71.6% required course) 4.1% No: (no plans for future) 8.1% (planned, opt) 0% (planned, reqd) 0%	(16.2%)

Fig. 1—Electrical engineering department replies.

Engineering Deans

Fig. 2 shows survey returns from engineering deans. Again, the per cent quantities are the percentage of

† Motorola, Inc., Western Military Electronics Center, Scottsdale, Ariz.

1 C.A. Krohn, "Reliability and engineering colleges," IRE Wescon Convention Record, Pt. 6, PP. 10–13; 1958.

he questionnaires returned that had the particular lank checked. Eighty-two questionnaires were re-urned. Percentage replies may be somewhat mislead-ng because all colleges do not have graduate divisions r all engineering disciplines shown.

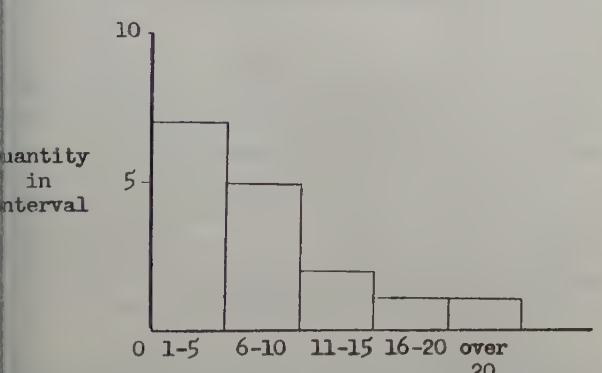
DISCUSSION

lectrical Engineering Departments

The extent of awareness and activity in reliabi-ity topics in electrical engineering curriculums is urprising. Approximately one-third of the schools esponding had some reliability treatment in existing nder-graduate courses. All of this was included in xisting circuits or systems courses. Fig. 3 shows e distribution of class room hours devoted to re-ability in these existing undergraduate electrical ngineering courses. As expected, most colleges had statistics course available to electrical engineering tudents (93.2 per cent), but only a few required it 5. 4 per cent).

	None Marked
1. Is a statistics course specifically designed for engineering topics available to engineering students?	
Ungrad Yes 47.5% No (planned for future) 19.5% No (not planned) 33%	0%
Grad Yes 43.9% No (planned for future) 14.6% No (not planned) 23.2%	18.3%
1a. If yes to 1, check the schools that require it?	
Ungrad EE4.9% ME4.9% CE4.9% IE32.9% ChE6.1% Phy 0% Chem 0% Other 12.2%	59.8%
Grad EE6.1% ME7.3% CE6.1% IE14.6% ChE4.9% Phy2.4% Other 8.5%	75.6%
2. Is any statistics course available to engineering students?	
Ungrad Yes 72% No (planned for future) 2.4% No (not planned) 2.4%	23.2%
Grad Yes 58.5% No (planned for future) 1.3% No (not planned) 1.2%	39%
2a. If yes to 2, check the schools that require it?	
Ungrad EE3.7% ME4.9% CE3.7% IE4.9% ChE6.1% Phy2.4% Chem2.9% Other 1.2%	86.7%
Grad EE1.2% ME1.2% CE2.4% IE 0% ChE1.2% Phy1.2% Chem1.2% Other 2.4%	96.5%

Fig. 2 — Engineering deans' replies.



g. 3 — Distribution of classroom hours devoted to reliability topics in existing electrical engineering courses.

The inclusion of reliability topics in existing elec-ical engineering courses is the desired approach in e opinion of the writer. Reliability attainment is best achieved when considered an implicit part of design, and such treatment in the engineering curriculum follows. Of the 67.5 per cent that do not have any reliability treatment in existing undergraduate electrical engineering courses, only 8 per cent are currently planning such activity. Thus, a fruitful area exists in selling electrical engineering departments on the need for inclusion of reliability topics. Similarly, the need of convincing electrical engineering departments to include an engineering statistics course is pointed out; of the 93.2 per cent of the colleges that have a statistics course available, only 5.4 per cent of the electrical engineering departments require it.

Engineering Deans

The primary mathematics used in quantitative reliability analysis is statistics. In the writer's opinion, inclusion of reliability topics in engineering courses is handicapped by the lack of familiarity of students and some teachers with statistics. Further, statistics is also necessary for pursuing other engineering topics, such as information theory. A questionnaire dealing only with statistics was sent to engineering deans.

Two-thirds of the replies (67 per cent) indicated they had or planned an undergraduate statistics course designed for engineering topics. However, as expected, few engineering disciplines required the course.

The engineering dean questionnaire was not clearly worded, and the author believes that some confusion existed in answering questions 2 and 2a. The objective of questions 2 and 2a was to establish whether statistics courses available to engineering students were of a general nature or designed for business or social study topics, as opposed to a statistics course designed especially for engineering topics. The author suggests that the replies to questions 2 and 2a be ignored, and that question 2 of the electrical engineering department questionnaire be used as an indication. Thus, from the electrical engineering department survey, around 93.2 per cent of engineering departments have an undergraduate statistics course available, and from question 1 of the engineering dean survey, around 47.5 per cent of these are especially designed for engineering topics.

Correspondence Received

Several letters were received from electrical engineering department spokesmen further elaborating on their views. These were about equally divided between extreme viewpoints. Some felt that reliability subjects and statistics were specific tool courses, and should or could not be included in the engineering program. The others had an opposite viewpoint, and were plan-

ning one or a series of courses on engineering for reliability and requiring one or more courses in statistics.

The author cannot agree with either of these extreme viewpoints. The mathematics of probability and statistics is no more a specific tool course than the mathematics of algebra, calculus, and differential equations. Information theory and realistic system design, as well as reliability topics, cannot be analytically treated without using probability concepts. Electrical circuit design is typically approached in the electrical engineering courses from the viewpoint that both passive and active component parameters will remain constant. Circuits designed in this manner that get into equipment result in equipment that continually fails. Somewhere in the electrical engineering circuit and network courses it should be pointed out that passive and active device parameters will vary considerably for different physical environments in a "statistical" manner, and analytical methodology (feedback is only one approach) for coping with this instability should be presented. Few would advocate that civil engineers should ignore the study of strength of materials and the ultimate utility of their designs, yet by ignoring the strength and stability of passive and active electrical components we electrical engineers are ignoring the ultimate utility of our designs.

As previously noted, the writer favors inclusion of reliability topics in existing circuit or system courses because reliability is best attained by designers considering reliability an implicit aspect of design. However, new topic areas often must be experimentally treated as separate courses before widespread acceptance occurs. As reliability is in this category, its treatment as a separate course is expected. More than one course in reliability and statistics appears to the writer as an intrusion on the already filled engineering program.

APPENDIX I

The following Quotations are from a previous Paper [1] of the Author.

INTRODUCTION

Reliability of electronic equipment during the past several years has been recognized by the electronics industry as a topic worthy of considerable attention. Many electronic companies have reliability groups, the engineering societies have formed professional groups in reliability, engineering publications have carried a vast number of papers on reliability, and many engineers are devoting their talents toward the topic of reliability.

Possible contributions of engineering colleges to widespread recognition of the need for improved reliability of electronic equipment and to widespread understanding of the methods to achieve improved reliability are considered in the following discussion. The discussion is pointed toward the undergraduate study of electronic engineering; however, the discussion is generally pertinent to curriculums for the undergraduate study of other branches of engineering and for graduate level electronic engineering.

CONCLUSION

With continued emphasis by the military on the achievement of reliability in electronic equipment that is supplied to them and the necessity for achieving reliable industrial electronic equipment for the era of automation to become a reality, it becomes increasingly important for the engineering graduates who will design this equipment to be cognizant of reliability fundamentals. Reliability analysis has progressed to the extent where it is suitable for treatment in engineering colleges.

Recommendations to electronic engineering schools are to introduce quantitative reliability techniques into various electronic courses, to add a course in engineering statistics, and to review various fundamental courses for possible reorientation toward achieving reliability. The electronics industry, through its reliability groups, is encouraged to offer assistance to the engineering colleges in the implementation of these recommendations.

APPENDIX II

QUESTIONNAIRE AND TEXT OF COVER LETTER SENT TO ELECTRICAL ENGINEERING DEPARTMENT HEADS

1. Is the subject of reliability treated in any E.E. course?
   Ungrad Yes: (optional course)____ (required course)____
   No: (no plans for future)____ (planned, opt)____ (planned, reqd)____
   Grad Yes: (optional course)____ (required course)____
   No: (no plans for future)____ (planned, opt)____ (planned, reqd)____

1a. If yes to 1, what type of course is it treated in and approx. how many class room hours are spent on it?
   Ungrad ____ Separate reliability course. Hours ____
   ____ Rel. included in ckt, sys, etc. crs. Hrs. (on rel) ____
   Grad ____ Separate reliability course. Hours ____
   ____ Rel. included in ckt, sys, etc. crs. Hrs. (on rel) ____

2. Is a statistics course available to E.E. students?
   Ungrad Yes: (optional course)____ (required course)____
   No: (no plans for future)____ (planned, opt)____ (planned, reqd)____
   Grad Yes: (optional course)____ (required course)____
   No: (no plans for future)____ (planned, opt)____ (planned, reqd)____

University ______________________ Signed ______________________

The lack of reliability in electronic equipment has been recognized as a problem of major importance. In particular is the seriousness of this in military electronic equipment. The United States Air Force reports that each year it spends double the initial cost of electronic equipment attempting to maintain this equipment. This lack of reliability is partly attributable to the design engineers virtually ignoring the reliability need.

Part of the answer to increasing equipment reliability is education of designers as to the need for high reliability and how to design for high reliability. Industry has been conducting various reliability education activities, and the area of reliability engineering has progressed to where it is capable of being studied in engineering colleges.

The enclosed paper, "Reliability and Engineering Colleges," was sponsored at the 1958 WESCON by the IRE Professional Group on Reliability and Quality Control. Suggestions are given in this paper as to how engineering colleges can orient engineering students toward equipment reliability improvement by teaching reliability as part of current courses. Various engineering colleges throughout the country have implemented these recommendations.

Recently the Electronics Division of the American Society for Quality Control contacted your Faculty Advisor for the AIEE and IRE student chapters offering him assistance on obtaining speakers for the student chapter in the area of reliability. Just a reminder that this offer of assistance remains.

Please complete and return the enclosed postal card questionnaire. Information obtained will be used as a guide to how industry can best assist engineering colleges in this area. If there is any way I can assist you in the reliability education area, please contact me.

APPENDIX III
JESTIONNAIRE AND TEXT OF COVER LETTER SENT TO ENGINEERING DEANS

. Is a statistics course specifically designed for engineering topics available to engineering students?
Ungrad: Yes____ No (planned for future)____ No (not planned)___
Grad: Yes____ No (planned for future)____ No (not planned)___

a. If yes to 1, check the schools that require it?
Ungrad: EE___ME___CE___IE___ChE___Phy___Chem___
Other___
Grad: EE___ME___CE___IE___ChE___Phy___Chem___
Other___

. Is any statistics course available to engineering students?
Ungrad: Yes____No (planned for future)____No (not planned)___
Grad: Yes____No (planned for future)____No (not planned)___

a. If yes to 2, check the schools that require it?
Ungrad: EE___ME___CE___IE___ChE___Phy___Chem___
Other___
Grad: EE___ME___CE___IE___ChE___Phy___Chem___
Other___

ersity ______________________ Signed ____________________

The lack of reliability in electronic equipment has been recognized as a problem of major importance. In particular is the seriousness of this in military electronic equipment. The United States Air Force reports that each year it spends double the initial cost of electronic equipment attempting to maintain this equipment. This lack of reliability is partly attributable to the design engineers virtually ignoring the reliability need.

Part of the answer to increasing equipment reliability is education of designers as to the need for high reliability and how to design for high reliability. Industry has been conducting various reliability education activities, and the area of reliability engineering has progressed to where it is capable of being studied in engineering colleges.

The enclosed paper, "Reliability and Engineering Colleges," was sponsored at the 1958 WESCON by the IRE Professional Group on Reliability and Quality Control. Suggestions are given in this paper as to how engineering colleges can orient engineering students toward equipment reliability improvement by teaching reliability as part of current courses. Various engineering colleges throughout the country have implemented these recommendations. The discussion in the paper is pointed toward electronic engineering, but the general points are pertinent to all branches of engineering.

Please complete and return the enclosed postal card questionnaire. Information obtained will be used as a guide to how industry can best assist engineering colleges in this area. If there is any way I can assist you in the reliability area, please contact me.

Improved Component Reliability Through a Comprehensive Program of Environmental Testing

S. J. KUKAWKA †

FOREWARD

As electronic circuitry becomes more complex l the need for system reliability becomes greater, cry for improved component reliability will be en louder than it has been during the past years. ticipating this requirement for components of pro- essively greater reliability and realizing that there no substitute for determining environmental per- mance other than the environmental tests them- ves, Bourns, Inc. launched a comprehensive test gram on production samples over two years ago. e continuing goal of this program is improved iability of the Trimpot lead screw actuated poten- meter.

SAMPLING PLAN

Perhaps the most difficult portion of any test gram is the establishing of a significant sampling n. Some of the variables that had to be considered he subject program are listed below:

1) Eight basic military specification lead screw actuated potentiometers are manufactured.
2) There is wide wirewound resistance range (10 to 50K in 12 standard resistances).
3) There is wide carbon resistance range (20K to 1 megohm in 6 standard resistances).
4) Almost all basic models are available in three terminal types, i.e., solder lugs, printed circuit pins, and flexible leads. This effectively tripled the number of models to be sampled.
5) Two manufacturing plants, eighteen hundred miles apart, produce most models concurrently.
6) Production volume varies monthly on most models.

It was first decided that MIL-STD-105A would be used to determine the minimum sample quantities for reliability assurance testing. Table V, the master table for reduced inspection, and inspection level I were applied. The variables mentioned above were resolved as follows:

ourns, Inc., Riverside, Calif.

1) Seven of the nine basic models are produced in high volume and are sampled monthly. The remaining two, specifically a high power unit and a twin potentiometer, are sampled quarterly because of the low production volume and their special nature.

2) and 3) Rather than sampling every resistance produced, the standard resistances were divided into groups or families which were considered to have comparable performance. These are tabulated in Table I.

TABLE I

WIREWOUND		CARBON	
Group	Resistance	Group	Resistance
I	10, 20, 50- -	VII	20K- -
II	100, 200, 500- -	VIII	50K, 100K, 200K- -
III	1K, 2K, 5K- -	IX	500K-Ω-
IV	10K, 20K- -	X	1 megohm

For a given sample period, one resistance is selected from each group. In groups containing two or more resistances, care is taken to sample different resistances each month.

4) Since internal construction, which is the greatest variable in environmental performance, is virtually identical for the three terminal types it was felt that any given terminal type would yield representative performance data for a given model. Accordingly, the three termination types are rotated from month to month, i.e., one month the flexible lead type is sampled, the second month the solder lug, and the third month, printed circuit pins, etc.

5) The two manufacturing plants are sampled independently. In order to maintain an even load on the test lab, one plant submits samples at mid-month and the other at the end of the month.

6) To eliminate production volume variations, the referenced MIL-STD-105A sampling plan is applied to a forecasted production volume. This forecast is reviewed every six months and revisions are made where necessary.

TEST AND TEST PROCEDURES

In the absence of a directly applicable military specification for lead screw actuated potentiometers, portions of test method specifications such as MIL-STD-202A and MIL-E-5272A, as well as rotary potentiometer specifications such as MIL-R-19A and MIL-R-94B are used. These procedures, modified when necessary to make them more practical for testing of lead screw actuated potentiometers, have been written up as Bourns Standard Test Procedures. An example of the high temperature stability and vibration standard test procedure are shown in Figs. 1 and 2. Since the choice of tests was large, two criteria were used in selecting those which would be ultimately used, the relative severity of the test and how nearly it approached a practical application. As a result of this study a group of monthly tests were decided upon. The sequence of testing as well as the division of the total sample is indicated by the following test groups.

Series A (All Samples Submitted)

Visual inspection,
total resistance tolerance,
end settings,
leadscrew torque,
effective rotation,
noise (wirewound potentiometers only),
continuity (carbon and wirewound potentiometers),
insulation resistance.

The above tests are a recheck of the final inspection each potentiometer undergoes before shipment or stocking. These tests also provide initial performance data for all subsequent test series.

Series B (40 Per Cent of Total Sample)

High temperature stability — exposure to the maximum operating temperature of the Trimpot® potentiometer for 24 hours.

Low temperature stability — exposure to -65°C for 24 hours.

Temperature cycling — five cycles per MIL-STD-202A, Method 102 except between -65°C and the maximum operating temperature of the potentiometer.

Dielectric strength — at room ambient pressure and simulated high altitude (80,000').

Series C (30 Per Cent of Total Sample)

Vibration — 20G or comparable displacement from 5 to 2000 cps in most models, 30G in certain high performance models. One hour in each of three mutually perpendicular axis.

Shock — in accordance with MIL-STD-202A, Method 202. 50G on most models, 100G on certain high performance models.

1000 TEMPERATURE

BOURNS, Inc. / *standard test procedure*

1001 High Temperature Stability, 24 Hours

INITIAL MEASUREMENTS

The wiper on all units tested shall be set at approximately 40% of total resistance. Voltage ratio and total resistance shall then be measured at room ambient conditions.

TEST CONDITIONS

Units shall be subjected to the maximum operating temperature specified (±5°C) for 45 ±15 minutes at which time the total resistance shall again be measured. (This resistance measurement shall be used for computing temperature coefficient). Care shall be taken to prevent accidental rotation of the shaft during measurement. The units shall then be left at this temperature for not less than 24 nor more than 26 hours.

FINAL MEASUREMENTS

After the measurement specified above, the units shall be returned to 25 +10, -5°C. After at least two hours, the total resistance and the voltage ratio shall be measured. Total resistance and voltage ratio shifts shall be computed by applying the following formulae:

$$\text{TR Shift} = \frac{(TR_f - TR_i) \times 100}{TR_i}$$

$$\text{VR Shift} = VR_f - VR_i$$

Where: "i" is initial reading at room conditions
"f" is final reading at room conditions

Temperature coefficient shall be calculated by applying the following formula:

$$TC = \frac{(R_2 - R_1) \times 100}{R_1 \ (T_2 - T_1)} = \frac{\%\ \text{TR Change}}{\text{Temp. Change}}$$

Where R_1 = Resistance in ohms at reference temperature (room conditions)
R_2 = Resistance in ohms at test temperature
T_1 = Reference temperature in degrees C
T_2 = Test temperature in degrees C

To be specified - Maximum Operating Temperature

Fig. 1.

3000 VIBRATION

BOURNS, Inc. / *standard test procedure*

3001 Vibration

MOUNTING

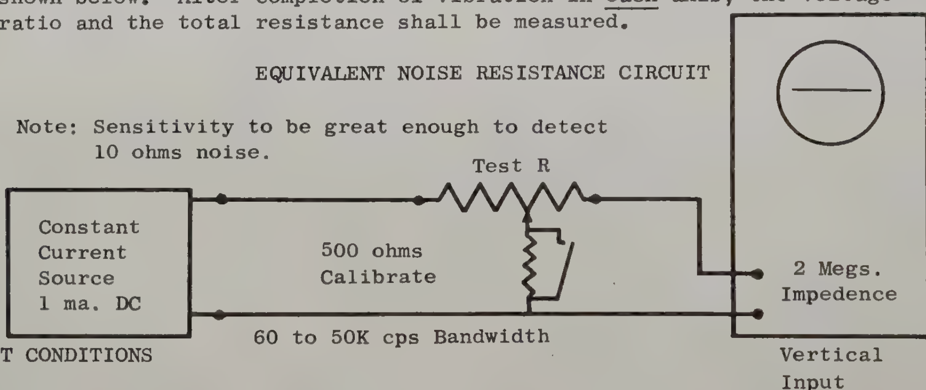
Wherever practical, units shall be mounted on the fixture according to standard mounting methods. Unless otherwise specified, models designed for mounting by terminals alone on printed circuit boards shall be so mounted. The mounting fixture shall be designed to permit rotation of the fixture in making a change of axis, rather than rotating individual units. Care shall be taken to prevent accidental rotation of the adjustment leadscrews during movement of the fixture.

MEASUREMENTS

Before testing, the wiper shall be moved to approximately 10% of total resistance. The voltage ratio and total resistance shall be recorded. During the tests, the wiper circuit shall be monitored by the circuit shown below. After completion of vibration in each axis, the voltage ratio and the total resistance shall be measured.

EQUIVALENT NOISE RESISTANCE CIRCUIT

Note: Sensitivity to be great enough to detect 10 ohms noise.



TEST CONDITIONS

The cycle specified below shall be repeated three times, once for each axis.

Units shall be vibrated throughout the frequency range and acceleration specified. The amplitude or acceleration shall be within ±10 per cent of the specified values. A complete sweep, up and back, shall be made within approximately 15 minutes for a total of 4 sweeps. Resonant frequencies, if any, shall be recorded. Units shall be vibrated 30 ±5 minutes at each resonant frequency observed. If four or more resonant frequencies are recorded, vibration shall be at those three frequencies at which resonance was of the greater magnitude.

To be specified - Displacement or Acceleration
Frequency Ranges

Fig. 2.

Series D (30 Per Cent of Total Sample)

Humidity — MIL-STD-202A, Method 102 on all applicable models. If model is not humidity proof, this sample is distributed among Series B and C.

Series E (Separate Sample Submitted Quarterly) terly)

Load life — per MIL-R-19A, 1000 hours,

Rotational life — 500 cycles throughout electrical travel.

MODEL 224

BOURNS, Inc. / *individual specification sheet*

Proc. No.	Test SERIES A	100	200	500	1K	2K	5K to 50K
		Nominal Total Resistance, Ohms					
101	Visual Inspection	Per outline drawing on reverse side					
201	Total Resistance tolerance	±5%	±5%	±5%	±5%	±5%	±5%
241	End Settings, max	.5Ω	.5Ω	.1%	.1%	.1%	.1%
301	Shaft Torque, in-oz.	0.2 - 5.0					
801	Effective Rotation, turns	22±2	22±2	22±2	22±2	22±2	22±2
401	Noise, ohms ENR max	100	100	100	100	100	100
501	Continuity	Smooth and unidirectional					
281	Insulation resistance, megohms min	1000	1000	1000	1000	1000	1000
	SERIES B						
1001	High temp. stability, 175°C						
	Temp. Coeff., Max, PPM/°C	70	70	70	70	70	70
	Total resistance shift, % max	1.1	1.0	1.0	1.0	1.0	1.0
	Voltage ratio shift, % max	1.1	0.9	0.7	0.6	0.5	0.5
1501	Low temp. stability, -65°C						
	Temp. Coeff., Max, PPM/°C	70	70	70	70	70	70
	Total resistance shift, % max	1.1	1.0	1.0	1.0	1.0	1.0
	Voltage ratio shift, % max	1.1	0.9	0.7	0.6	0.5	0.5
2001	Temperature Cycling, Step 3, 125°C						
	Total resistance shift, % max	1.1	1.0	1.0	1.0	1.0	1.0
	Voltage ratio shift, % max	1.1	0.9	0.7	0.6	0.5	0.5
9001	Dielectric Strength						
	Sea Level, min VAC	1500	1500	1500	1500	1500	1500
9011	Dielectric Strength						
	80,000 ft., min VAC	500	500	500	500	500	500
	SERIES C						
3001	Vibration...						
	.5"da, 5-35cps; 30G, 35-2000cps						
	Noise, ohms ENR, max.	10	10	10	10	10	10
	Total resistance shift, % max	1.1	1.0	1.0	1.0	1.0	1.0
	Voltage ratio shift, % max	1.1	0.9	0.7	0.6	0.5	0.5
4001	Shock, 100G						
	Total resistance shift, % max	1.1	1.0	1.0	1.0	1.0	1.0
	Voltage ratio shift, % max	1.1	0.9	0.7	0.6	0.5	0.5

Proc. No.	Test SERIES D	100	200	500	1K	2K	5K to 50K
		Nominal Total Resistance, Ohms					
9051	Effects of Soldering, S&P Only						
	Total resistance shift, % max	2.0	2.0	2.0	2.0	2.0	2.0
5001	Load life						
	70°C, watts	1.0	1.0	1.0	1.0	1.0	1.0
	Total resistance shift, % max	2.0	2.0	2.0	2.0	2.0	2.0
	Continuity	Smooth and unidirectional					
6001	Rotational life:						
	200 cycles						
	Total resistance shift, % max	2.0	2.0	2.0	2.0	2.0	2.0
	500 cycles						
	Continuity	Smooth and unidirectional					
	SERIES E						
7001	Humidity						
	Total resistance shift, % max.	2.0	2.0	2.0	2.0	2.0	2.0
	Insulation resistance, megohms minimum	100	100	100	100	100	100

Subject to Change Without Notice

Note: Consult Manufacturer if Special Specification Tolerances are Required

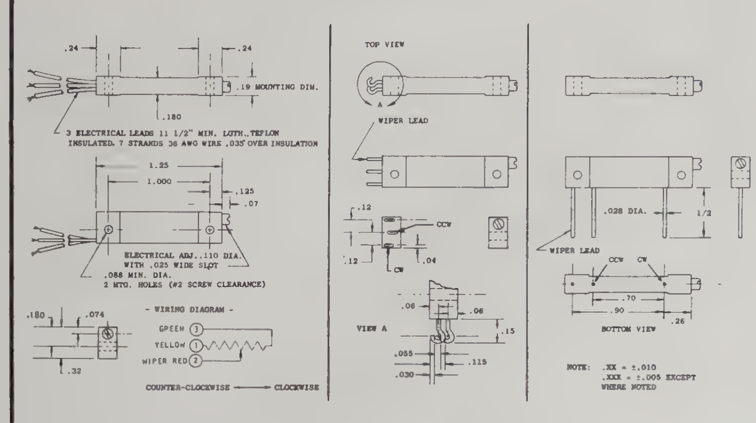


Fig. 3.

In addition to the above, certain other tests are performed on a reduced sample. These are
resolution of wirewound potentiometers,
terminal pull test,
printed circuit pin bending test.

PERFORMANCE SPECIFICATIONS

In order to clearly define the performance specifications in the environmental tests, individual specification sheets (ISS) were prepared for each model. Fig. 3 shows a typical ISS. Temperature coefficients, shift specifications, etc., are shown for each test. Since in low resistance wirewound units shift specifications often read a given value "or resolution", the resolution shift for these resistances is shown. The ISS also contains an outline drawing which is used during the visual inspection.

DATA HANDLING AND ANALYSIS

Since approximately 260 Trimpot potentiometers are tested each month, involving between 1300 and 1500 individual performance figures, it became obvious that a fast means of data handling would be necessary, particularly if frequency distribution tabulations were desired. Accordingly, provisions were made to punch this data into IBM cards, which could be very quickly tabulated when necessary. The resultant frequency distribution information yielded curves of performance such as those shown in Fig. 4. After this method of data handling had been in operation for over a year it became obvious that not all performance parameters were indicative of component reliability. Certain key areas and tests were selected for careful scrutiny whereas other data was analyzed in more cursory manner. With this reduced need for frequency distribution tabulations, the IBM system was temporarily discontinued. Data is still gathered in a form readily adaptable to the reinstitution of this system when it becomes necessary.

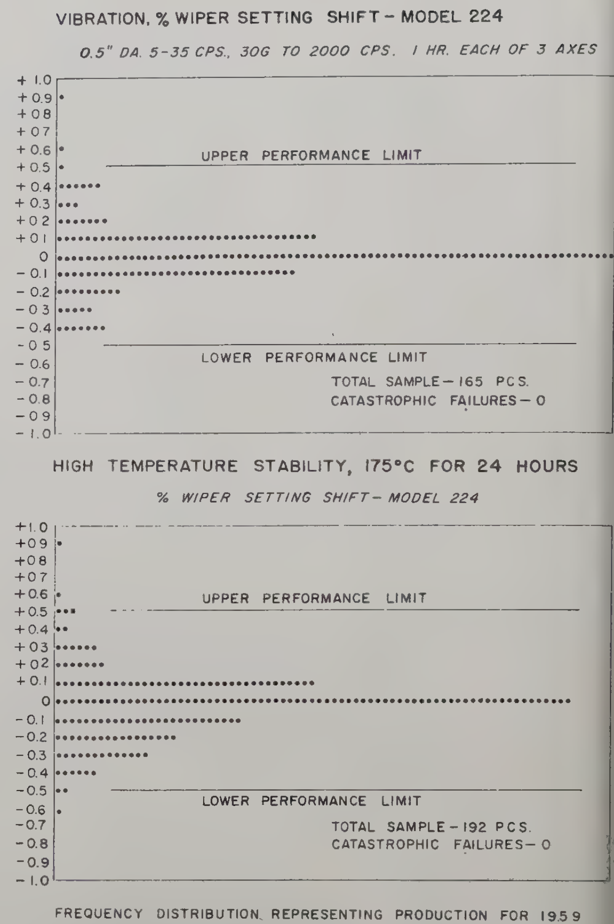


Fig. 4—Frequency distribution representing production for 1959.

CORRECTIVE ACTION ON FAILURES

Perhaps the most important and most valuable aspect of this whole program is the determination of failure modes. These various problem areas can then be worked upon and eliminated one by one. The test laboratory, where reliability assurance tests are performed, is in constant contact with both manufacturing plants. If unusual performance is noted or if failures occur, the respective plant is notified immediately, whereupon analysis is made and corrective action is taken. Thus, through an extensive program of environmental testing of production samples, rapid analysis of test data and test samples, and immediate corrective action when necessary, the reliability of the Trimpot potentiometer has been and is continually being improved.

CONCLUSION

Described here is the approach of one components manufacturer, Bourns, Inc., to the industry demand for improved component reliability. It is felt that the subject program, with appropriate modifications, can be applied to almost any electronic component. If the adoption of these ideas contributes to the advancement of the "state of the art" in the component industry, the purposes of this paper have been fulfilled.